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ELASTIC-PLASTIC RESPONSE CHARTS FOR NUCLEAR OVERPRESSURES

by

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The single-degree-of-freedom equation of motion for an elastic-plastic system with forcing functions that are representative of nuclear weapon simulations is nondimensionalized and solved. Numerical solutions are calculated by the Newmark β method, and response charts incorporating nondimensionalized structural and loading parameters for the Speicher-Brode nuclear pressure history description are provided. A computer code is presented for solving the elastic-plastic problem for Speicher-Brode overpressure as well as triangular-shaped overpressures.

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PREFACE

The preparation of this report was sponsored by the Defense Nuclear Agency (DNA) under Subtask Y99QAXSC, Work Unit 00080, "Key Worker Shelter," and by the Office, Chief of Engineers, U. S. Army, under R&D Project 4A762719AT40, Task AO, Work Unit 008, "Target Response from Low-Yield Nuclear Surface and Subsurface Bursts." Dr. K. L. Goering, DNA, was Technical Monitor.

This report was prepared at the Structures Laboratory (SL), U. S. Army Engineer Waterways Experiment Station (WES), under the general supervision of Mr. Bryant Mather, Chief, SL, and Mr. James T. Ballard, Acting Assistant Chief, SL, and under the direct supervision of Dr. Jimmy P. Balsara, Acting Chief, Structural Mechanics Division (SMD), SL. This paper was prepared by Mr. L. K. Guice, Associate Professor, Louisiana Tech University, and Dr. S. A. Kiger of the Research Group, SMD.

COL Tilford C. Creel, CE, was Commander and Director of WES during this study and the preparation and publication of this report. Mr. F. R. Brown was Technical Director.

CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

CONVERSION FACTORS, NON-SI TO SI (METRIC) UNITS OF MEASUREMENT

Non-SI units of measurement used in this report can be converted to SI (metric) units as follows:

Multiply	By	To Obtain
inches	2.54	centimetres
kilofeet	0.3048	kilometres
kilotons (nuclear equivalent of TNT)	4.184	terajoules
pounds (mass)	0.45359237	kilograms
pounds per square inch	6.894757	kilopascals
pounds per square inch per second	6.894757	kilopascals/second
tons (nuclear equivalent of TNT)	4.184	gigajoules

RESPONSE OF AN ELASTIC-PLASTIC STRUCTURE SUBJECTED TO A SIMULATED NUCLEAR BURST

CHAPTER 1

INTRODUCTION

Very few structures are designed to remain elastic under highly impulsive loads. Systems that are designed to behave elastically under such loads are generally uneconomical and tend to have structural characteristics that attract greater dynamic forces. Consequently, some plastic behavior is desirable for the largest dynamic loads that are anticipated to occur.

The stress distribution in a structure that undergoes a plastic response is complex and difficult to predict. Hence, the design and failure criteria for such structures are generally governed by limitations on response, e.g., deflections and rotations, rather than by limitations on stresses.

This paper presents the mathematical model and the numerical solution for the response of structures that behave as elastic-perfectly plastic systems when subjected to monotonically decaying loads. The loading definition is intended to simulate the pressure-time history of a nuclear pulse with zero rise time and no negative phase.

CHAPTER 2

ANALYTICAL PROCEDURE

2.1 DEFINITIONS OF DUCTILITY AND RESISTANCE

A measure of the total elastic and plastic deformation in a structure is its ductility. In this paper, ductility will be defined as the ratio of the maximum displacement under a prescribed load to peak elastic displacement, i.e., x_m/x_y[1] in Figure 2.1. The maximum ductility that a structure can sustain without collapse is controlled by its material and geometric characteristics and is an indicator of the amount of energy that can be absorbed prior to failure.

The relationship between static load and deflection, i.e., the resistance function, for many structural elements may be idealized as the elastic-perfectly plastic curve shown in Figure 2.1. For monotonic dynamic loads, it is generally assumed that the resistance function maintains the same characteristic form as for the static situation. However, the magnitudes may be increased to represent the enhanced strength of the material under the high strain rates associated with dynamic loads.

2.2 DESCRIPTION OF LOAD

In the past, nuclear pressure histories have often been represented as simple triangular functions or as superimposed combinations of simple triangles (References 1 and 2). Analyses made with such loading definitions have often proved to be reliable, particularly when the loads are most impulsive or when the duration of the load is large compared to the natural period of the structure. However, when attempting to represent some nuclear weapon loadings, the use of an "equivalent" triangular function introduces significant error. The selection of an appropriate triangle to represent a particular nuclear pulse adds one more degree of uncertainty to the already subjective dynamic analysis.

Analytic approximations to actual nuclear burst overpressures have recently been developed. The most recent expression for the overpressures can

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[1]For convenience, symbols and unusual abbreviations are listed and defined in the Notation (Appendix C).

be found in Reference 3 with subsequent modifications by memoranda from the authors. The Speicher-Brode fit relates height of burst, range, time of arrival, positive phase duration, and overpressure for a 1-kiloton[2] (KT) weapon. Calculation of the quantities listed above, as well as positive phase impulse, for a 1 megaton (MT) surface burst weapon are included in Table 2.1 and Figure 2.2. Cube-root scaling can be used to relate the quantities of interest for different weapon yields.

2.3 STRUCTURAL IDEALIZATION

Many structures may be idealized as single-degree-of-freedom (SDOF) spring-mass models in order to determine their fundamental response. More complex structures may be idealized as a combination of spring-mass models that are superimposed by modal superpositioning. The idealized SDOF model used in this paper, as well as the resistance and loading idealizations, are shown in Figure 2.1.

The differential equation of motion for the undamped SDOF model is given below.

$$m\ddot{x} + kx = F(t) \qquad (2.1)$$

where

$\ddot{x} = d^2y/dt^2$ = acceleration

and $kx = r_m$, if plastic response has occurred

Viscous damping is generally not included in the analysis of structures that are subjected to short-duration monotonic loads, particularly when only the peak response is of primary interest. Damping at less than 5 or 6 percent of critical will have only a minor effect on peak response for nonoscillating loads.

Equation 2.1 can be nondimensionalized by a transformation of the independent variables to yield the following equations from Reference 2.

$$\frac{1}{4\pi^2}\ddot{\eta} + \eta = \frac{F_1}{r_m} f(\xi) \text{ , if elastic,} \qquad (2.2)$$

[2] A table of factors for converting U. S. customary units of measurement to metric (SI) units is presented on page 4.

and

$$\frac{1}{4\pi^2}\ddot{\eta} + 1 = \frac{F_1}{r_m} f(\xi) \text{ , if plastic,} \tag{2.3}$$

where

$$\eta(\xi) = x(t)/x_y$$

$$\ddot{\eta}(\xi) = T^2\ddot{x}(t)/x_y$$

$$\xi = t/T$$

$$x_y = \text{displacement at first yield}$$

$$T = 2\pi\sqrt{\frac{m}{k}} = \text{natural period}$$

It should be noted that the specified forcing function in Equations 2.2 and 2.3 implies that pressures may be normalized with respect to a single time parameter. However, the Speicher-Brode loading definition is a function of time and of peak overpressure and may not be normalized by a single parameter as illustrated in Figure 2.3. Thus, a separate response chart must be developed for each value of peak overpressure, P_s.

2.4 NUMERICAL SOLUTION

There are several numerical methods for solving the nondimensionalized equations of motion. A method that is frequently applied to problems in structural dynamics is the Newmark β method (Reference 4). This method was selected for numerical analysis because of its flexibility and established criteria for stability and convergence.

From previously defined relationships, we have

$$x(t) = x_y\eta(\xi)$$

$$\dot{x}(t) = x_y\dot{\eta}(\xi)/T$$

$$\ddot{x}(t) = x_y\ddot{\eta}(\xi)/T^2$$

$$\xi = \frac{t}{T}$$

For our initial conditions

$$\eta_o = 0$$

$$\dot{\eta}_o = 0$$

The initial value of the acceleration term is

$$\ddot{\eta}_o = 4\pi^2 F_1/r_m$$

The Newmark β equations may be written in nondimensionalized form as indicated below:

$$\eta_{i+1} = \eta_i + \left(\frac{\Delta t}{T}\right)\dot{\eta}_i + (1/2 - \beta)\left(\frac{\Delta t}{T}\right)^2 \ddot{\eta}_i + \beta\left(\frac{\Delta t}{T}\right)^2 \ddot{\eta}_{i+1} \qquad (2.5)$$

$$\dot{\eta}_{i+1} = \dot{\eta}_i = 1/2\left(\frac{\Delta t}{T}\right)\left(\ddot{\eta}_i + \ddot{\eta}_{i+1}\right) \qquad (2.6)$$

By making an assumption for the acceleration at the (i+1) time step, approximations of the corresponding displacement and velocity terms can be made with the equations above. The resulting displacement can then be inserted into the original differential equation and tested for convergence. The process may be repeated iteratively until convergence is met within a prescribed tolerance.

Criteria for selecting an appropriate normalized time increment ($\Delta t/T$) should not be based solely upon the value of β , i.e., the implied assumption of acceleration between time steps, but should also depend upon the duration of the load. Sufficiently small time steps must be used to provide an appropriate description of the loading function.

As an example of the numerical parameters which might be used: for linear acceleration, $\beta = 1/6$; the normalized time increment limit for convergence = 0.389; and the normalized time increment limit for stability = 0.551 (Reference 4). Also, the time increment typically should not exceed about 1/10 of the duration of the load.

Table 2.1. Speicher-Brode relationships for a 1-MT surface burst weapon.

PSO - Surface overpressure (psi)

R - Range (kft)

t_a - Time of arrival (ms)

t_d - Positive phase duration (ms)

I_p - Positive phase impulse (psi-ms)

PSO	R	t_a	t_d	I_p
1.0	46.767	34,939.3	4,376.8	1,955
2.0	28.025	18,646.6	3,930.7	3,285
3.0	21.122	12,797.8	3,583.2	4,301
4.0	17.505	9,817.7	3,308.3	5,136
5.0	15.248	8,009.4	3,085.3	5,852
6.0	13.685	6,790.6	2,900.1	6,482
7.0	12.527	5,910.1	2,743.4	7,043
8.0	11.627	5,242.1	2,608.7	7,548
9.0	10.903	4,717.0	2,491.5	8,004
10.0	10.304	4,292.4	2,388.5	8,415
20.0	7.264	2,310.1	1,785.3	10,596
30.0	6.009	1,609.0	1,519.1	11,366
40.0	5.282	1,245.9	1,378.0	12,741
50.0	4.794	1,022.5	1,297.1	14,598
60.0	4.437	870.6	1,249.3	16,469
70.0	4.161	760.2	1,221.5	17,986
80.0	3.939	676.2	1,206.2	18,969
90.0	3.755	610.0	1,199.1	19,482
100.0	3.600	556.4	1,197.5	19,743
200.0	2.752	305.0	1,274.3	28,198
300.0	2.366	215.1	1,357.8	35,047
400.0	2.131	167.9	1,418.5	38,823
500.0	1.967	138.6	1,461.9	42,076
600.0	1.844	118.4	1,493.2	45,206
700.0	1.746	103.7	1,516.2	48,225
800.0	1.666	92.4	1,533.3	51,112
900.0	1.599	83.4	1,546.0	53,856
1,000.0	1.541	76.1	1,555.5	56,460
2,000.0	1.214	41.5	1,575.7	76,529
3,000.0	1.058	28.9	1,557.8	90,071
4,000.0	0.960	22.3	1,535.2	100,208
5,000.0	0.891	18.3	1,513.2	108,274
6,000.0	0.838	15.5	1,493.1	114,954
7,000.0	0.796	13.4	1,474.9	120,646
8,000.0	0.761	11.9	1,458.4	125,602
9,000.0	0.732	10.7	1,443.4	129,994
10,000.0	0.707	9.7	1,429.7	133,940

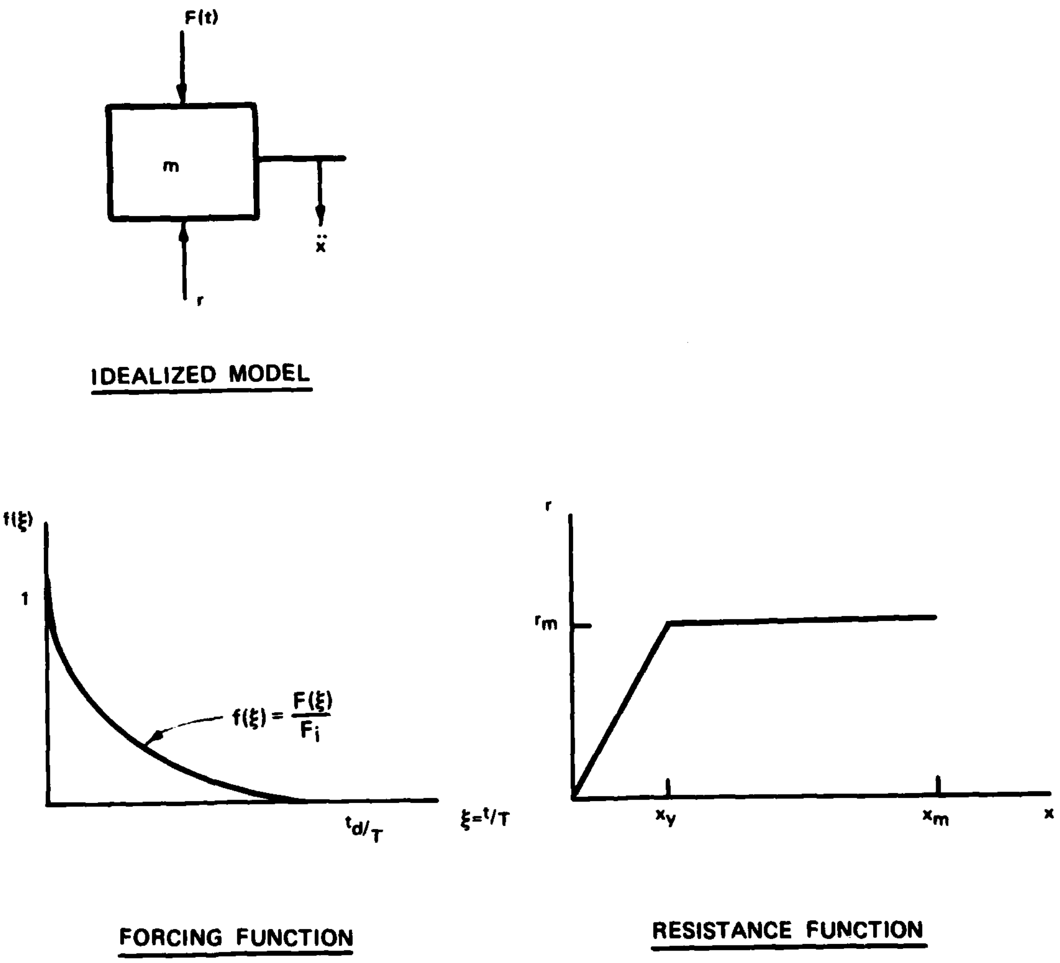


Figure 2.1. SDOF analytical model.

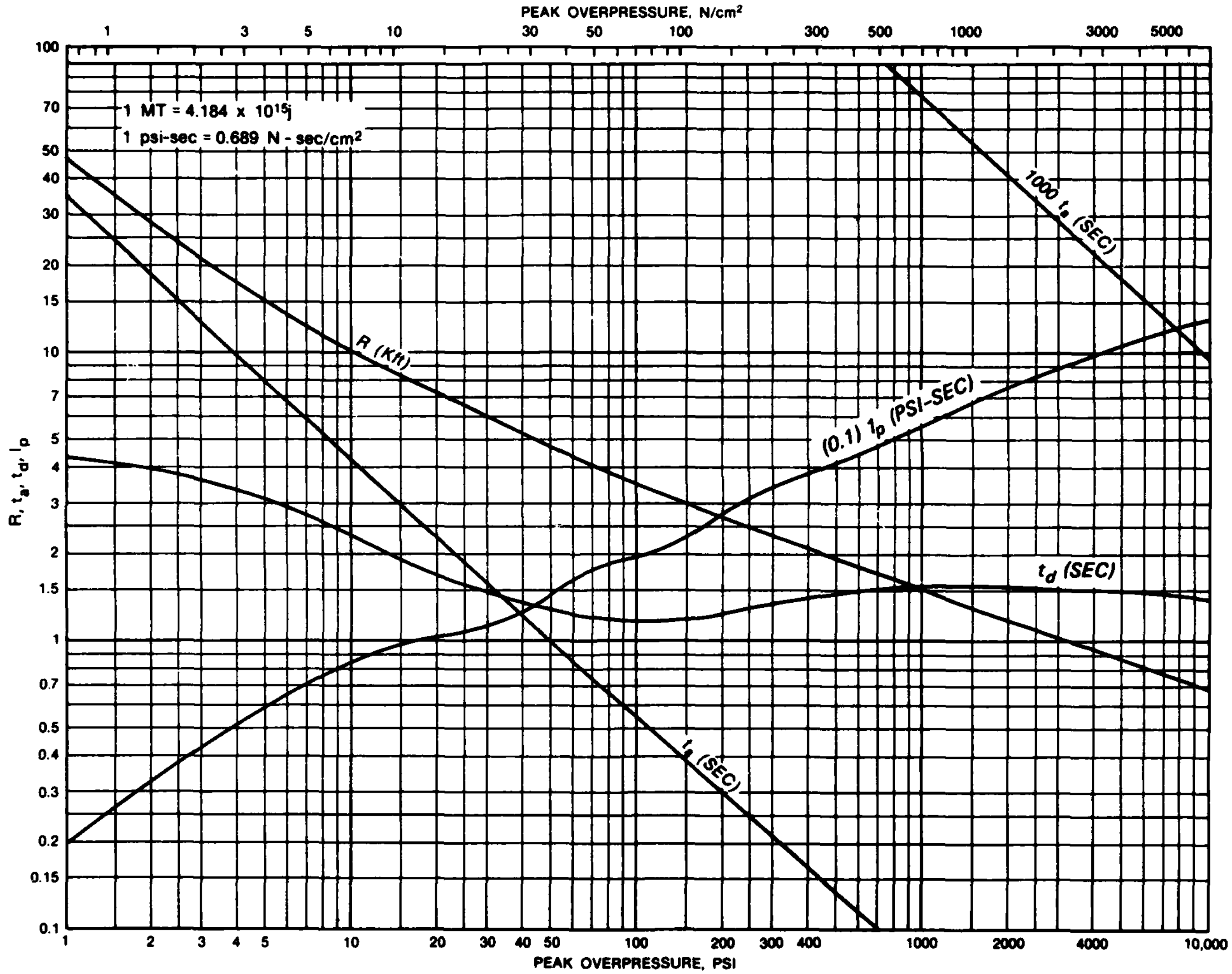
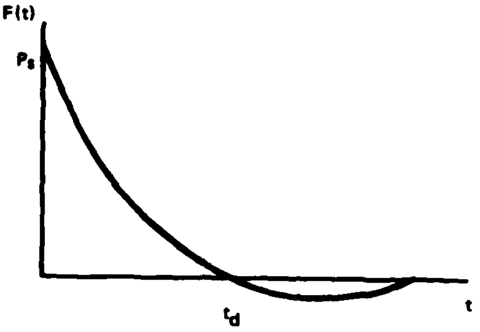
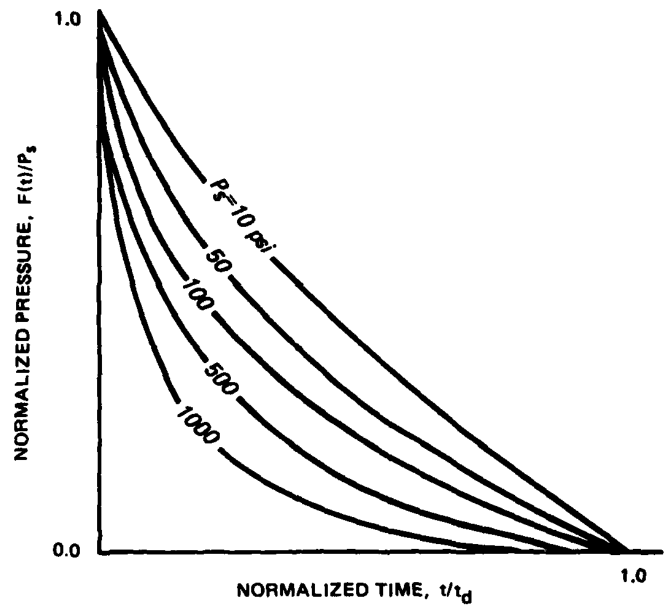


Figure 2.2. Speicher-Brode relationships for a 1-MT surface burst weapon.



a. Nuclear overpressure decay curve.



b. Normalized pressure history.

Figure 2.3. Typical overpressure decay curves for a specific nuclear weapon at various overpressures.

CHAPTER 3

SOLUTIONS

3.1 RESPONSE CHARTS

Once the differential equations have been nondimensionalized, the solutions can be plotted over specific ranges of the nondimensionalized parameters to produce a practical design tool. Normalized response charts for triangular loads (Reference 2) and bilinear loads (Reference 5) are available in the open literature.

Charted solutions for the Speicher-Brode overpressure description are provided in Figures 3.1-3.9. It should be repeated that because the normalized pressure history definition is a function of two independent variables, i.e., time and peak overpressure, a unique solution to the differential equation cannot be obtained. However, uniqueness was obtained in this case by holding the peak overpressure constant, thereby creating an equation with a single independent variable. As a result, separate charts were plotted for each peak overpressure.

3.2 SOLUTION ACCURACY

Response charts are provided for peak overpressures ranging from 10 psi to 50,000 psi. For design purposes, reasonable accuracy may be obtained at intermediate overpressures by interpolating between the given charts. If more accurate solutions are desired, a computer code is provided in Appendix A that will give numerically accurate solutions for any desired overpressure.

A comparison of solutions obtained from the response charts with solutions obtained from the computer code has indicated that logarithmic interpolation formulas will in general provide more accurate solutions between respective charts. Although linear interpolation between any of the charts will provide reasonable answers, more accurate solutions can sometimes be obtained with logarithmic interpolation formulas. Appropriate interpolation formulas are presented in Table 3.1.

3.3 EXAMPLE PROBLEMS

The number of ways that the response charts may be used are too numerous to sufficiently describe here. In addition to the fact that the user may

enter the charts with several different combinations of input parameters, there are many different ways to arrive at those parameters themselves, e.g., natural period, yield deflection, and maximum resistance. Hence, the following examples are only provided to illustrate the actual mechanics of using the charts. It is assumed that the user will know how to compute the basic properties of the physical model.

In this example, the maximum response is determined for a system with a natural period of 0.300 seconds, a maximum resistance of 10 psi, and a peak elastic deflection of 0.5 inch. The structure is subjected to a 20-KT surface burst weapon at 25 psi.

In the response curves, the natural period of the structure has been normalized with respect to the positive phase duration of the load. To find the positive phase duration for the prescribed loading, see Figure 2.2 (t_d = 1.6 seconds).

By cube-root scaling, the duration of a 20-KT weapon is computed as

$$\frac{t_d}{1.6\ \mathrm{s}} = \left(\frac{20\ \mathrm{KT}}{1{,}000\ \mathrm{KT}}\right)^{1/3}$$

$$t_d = 0.434\ \mathrm{s}$$

Computing the response chart input parameters

$$\frac{t_d}{T} = \frac{0.434}{0.300} = 1.45$$

$$\frac{P_s}{r_m} = \frac{25}{10} = 2.50$$

Now, entering the 10-psi response chart (Figure 3.1)

$$\mu_{10} = \frac{x_m}{x_y} = 16$$

and, entering the 50-psi response chart (Figure 3.2)

$$\mu_{50} = 6.5$$

Interpolating (Table 3.1)

$$\mu_{25} = \exp\left[\frac{\ln\left(\frac{25}{50}\right)}{\ln\left(\frac{10}{50}\right)} \cdot \ln\left(\frac{16}{6.5}\right) + \ln(6.5)\right] = 9.58$$

The predicted maximum response is

$$x_m = \mu_{25} x_y = 9.58\ (0.5\ \text{inch}) = 4.79\ \text{inches}$$

Similarly, the estimated time to maximum response is

$$t_m = 0.38\ \text{second}$$

The maximum response as determined directly by computer analysis is indicated in Appendix B. In this case, there is an interpolation error of approximately 2 percent. Using a linear interpolation, the maximum response would be predicted as $\mu = 12.4$, which is an error of approximately 32 percent.

In a second example, consider a system with a natural period of 0.50 second and a maximum resistance of 50 psi. Using a 75-KT weapon, the peak overpressure for which the structure can maintain a ductility of 15 may be obtained by the following procedure.

Assume a peak overpressure of 100 psi. From Table 2.1, the positive phase duration for a 1-MT weapon is 1.198 seconds. For a 75-KT weapon, the duration is scaled as follows:

$$\frac{t_d}{1.198\ \text{s}} = \left(\frac{75\ \text{KT}}{1{,}000\ \text{KT}}\right)^{1/3}$$

$$t_d = 0.505\ \text{s}$$

Now, computing the nondimensionalized parameters based on the assumed overpressure

$$\frac{t_d}{T} = \frac{0.505}{0.050} = 10.1$$

$$\frac{P_s}{r_m} = \frac{100}{50} = 2.0$$

Using the 100-psi response chart, a ductility of 28 is read. That is higher than our limiting ductility. Therefore, try a lower peak overpressure of 50 psi (Figure 3.2). The positive phase duration of 1.297 seconds for a 1-MT weapon at 50 psi scales to 0.547 second for a 75-KT weapon.

The new input parameters are

$$\frac{t_d}{T} = \frac{0.547}{0.050} = 10.9$$

$$\frac{P_s}{r_m} = \frac{50}{50} = 1.0$$

From the 50-psi response chart (Figure 3.2), a much lower ductility of 3.2 is read. Finally, interpolating between the 50- and 100-psi values (Table 3.1)

$$P_s = \frac{(15 - 3.2)}{(28 - 3.2)} \cdot (100 - 50) + 50$$

$$P_s = 74 \text{ psi}$$

The correct solution was determined by computer analysis to be approximately 77 psi. The interpolation error is approximately 4 percent.

3.4 COMPUTER CODE

The code provided in Appendix A was written in Fortran for the Tektronix 4081. It is an interactive code that has been modularized to minimize memory requirements. The code should be easily adaptable to other machines with modification or elimination of the plot routines and overlay structure. The user should also find it quite simple to add alternate loading definitions to the code, if so desired.

Upon initialization of the program, a list of the available user options is displayed to the screen. These options and a brief description of each follow. A sample session is included in Appendix B.

X - EXIT PROGRAM - The user may exit the program any time there is a request to SELECT OPTION.

A - ANALYZE - The Newmark β analysis is performed and results are displayed. A complete response history including normalized displacements, velocities, and accelerations may be optionally displayed.

D - DISPLAY DATA - All numerical parameters, the current loading description, and structural parameters are displayed to the screen.

H - HELP - A list of the available options is provided upon request.

I - INITIAL PASS - This option assists the new user in making a first run through the program. The experienced user may find it to be a beneficial option when no modifications in the numerical parameters are required prior to analysis.

L - LOADING FUNCTION - The user may select a Speicher-Brode or triangular loading description. The weapon, peak overpressure, and height of burst are requested if the Speicher-Brode description is selected. Peak overpressure and duration are requested for the triangular function.

N - NUMERICAL PARAMETERS - Certain numerical parameters may be changed by the user. The values of Beta, the integration increment, the convergence tolerance, and the number of pressure stations to be computed may be changed by selecting this option. Default values are displayed.

O - OUTPUT DEVICE - When large quantities of data are to be output, the user may select for that data to be routed to the printer.

P - PLOT - Normalized displacements, velocities, accelerations, and a description of the loading function may be displayed in graphical form upon request.

S - SET VALUES FOR ANALYSIS - The natural period of the structure and its peak resistance are requested by this option.

T - TITLE - Output data and plots display a title that may be changed by selecting this option.

Table 3.1. Interpolation formulas.

Type of Interpolation	To Find	Formula	Suggested Ranges (psi)
Linear	μ	$\mu_{P_s} = \dfrac{(P_s - P_{s1})}{(P_{s2} - P_{s1})} \cdot (\mu_2 - \mu_1) + \mu_1$	50-100
	P_s	$P_s = \dfrac{(\mu_{Ps} - \mu_1)}{(\mu_2 - \mu_1)} \cdot (P_{s2} - P_{s1}) + P_{s1}$	
Natural logarithmic	μ	$\mu_{P_s} = \exp\left[\dfrac{\ln\left(\dfrac{P_s}{P_{s2}}\right)}{\ln\left(\dfrac{P_{s1}}{P_{s2}}\right)} \cdot \ln\left(\dfrac{\mu_1}{\mu_2}\right) + \ln(\mu_2)\right]$	10-50 100-200 200-500 500-1,000 1,000-10,000 10,000-20,000 20,000-50,000
	P_s	$P_s = \exp\left[\dfrac{\ln\left(\dfrac{\mu_{Ps}}{\mu_2}\right)}{\ln\left(\dfrac{\mu_1}{\mu_2}\right)} \cdot \ln\left(\dfrac{P_{s1}}{P_{s2}}\right) + \ln(P_{s2})\right]$	

Notation: P_s - overpressure for which solution is desired
P_{s1} - overpressure of response chart before P_s
P_{s2} - overpressure of response chart after P_s
μ_{ps} - ductility at desired overpressure
μ_1 - ductility from response chart before P_s
μ_2 - ductility from response chart after P_s

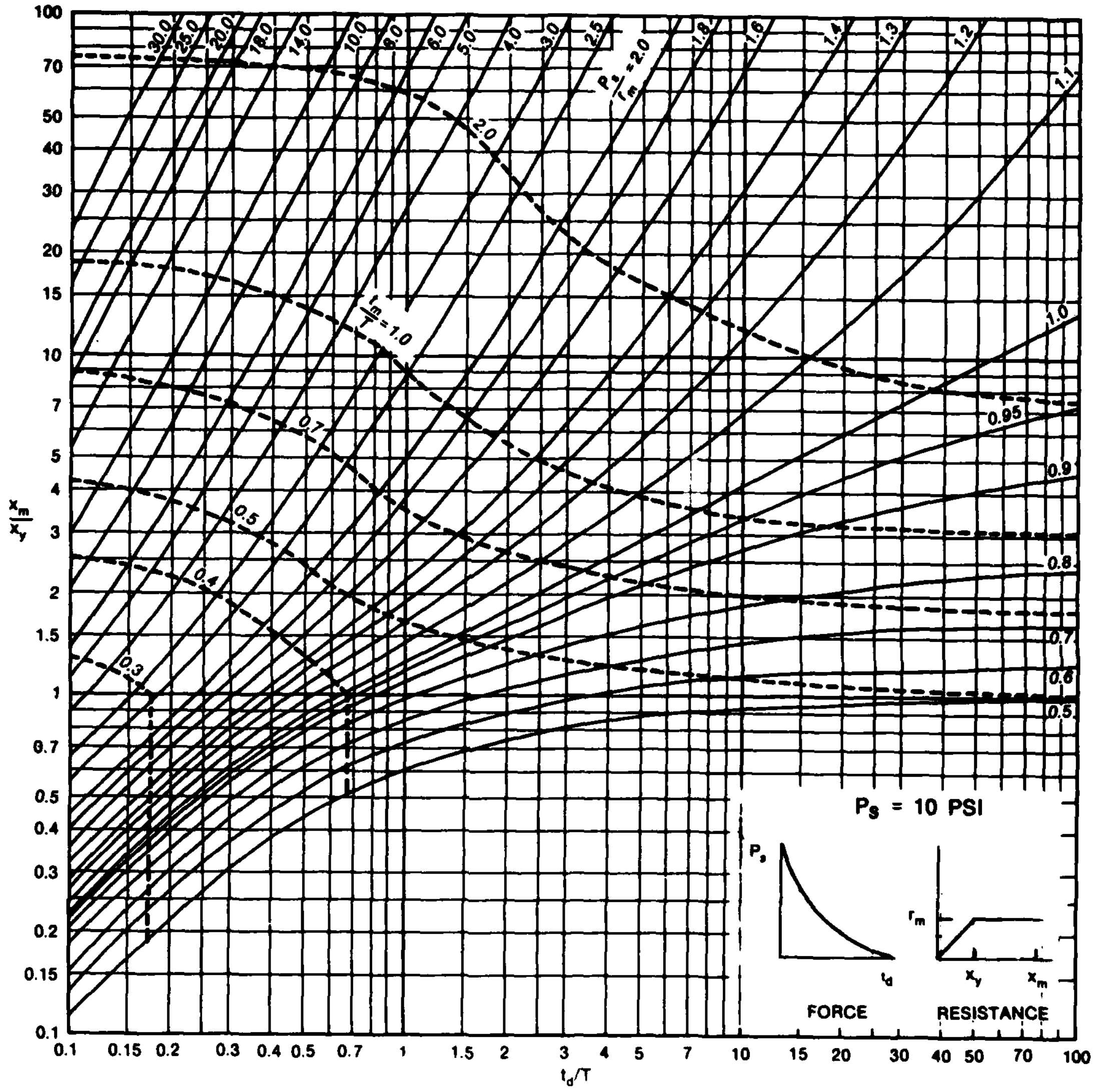


Figure 3.1. Maximum response of an elastic-plastic system subjected to a 10-psi Speicher-Brode pulse.

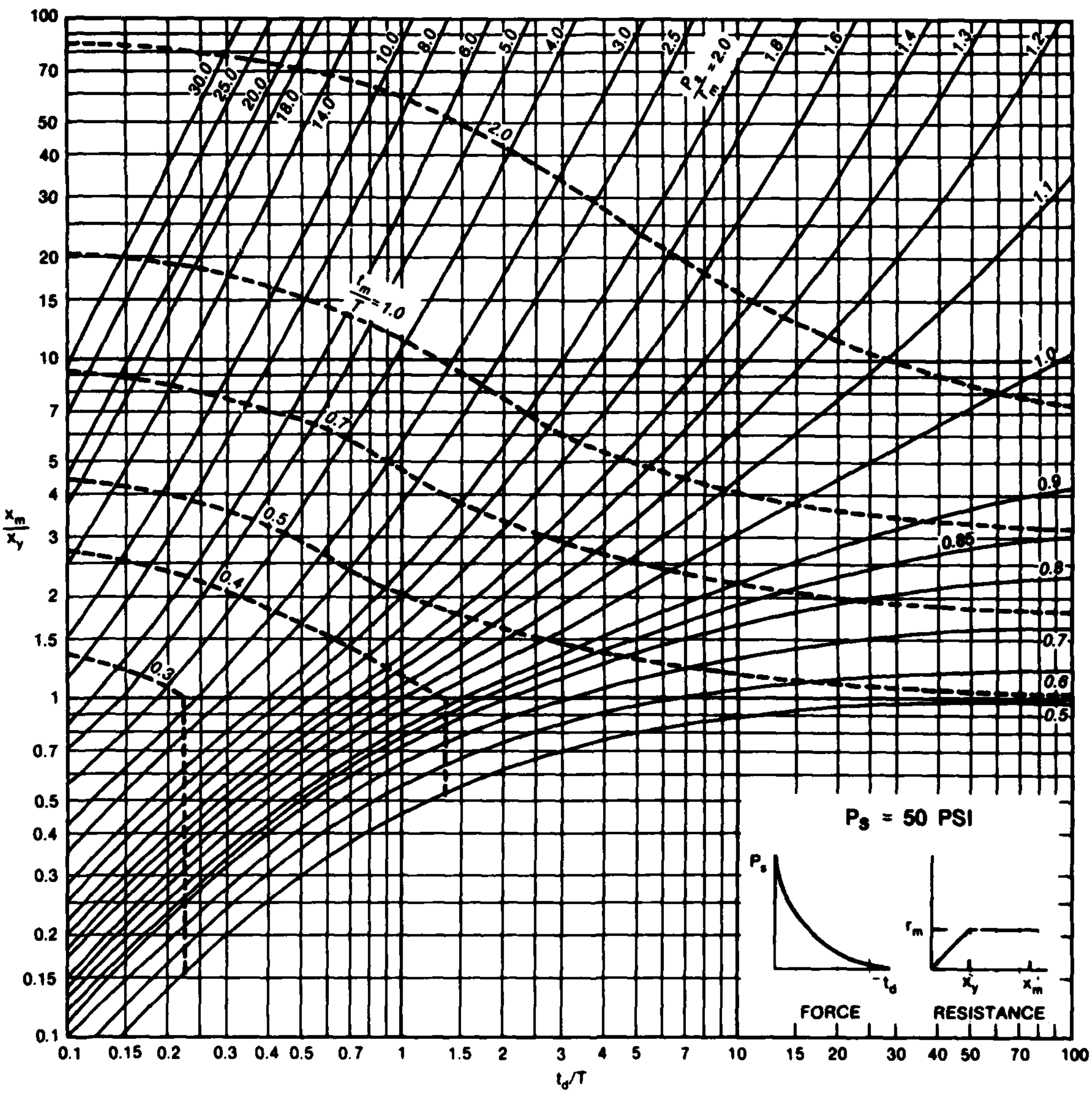


Figure 3.2. Maximum response of an elastic-plastic system subjected to a 50-psi Speicher-Brode pulse.

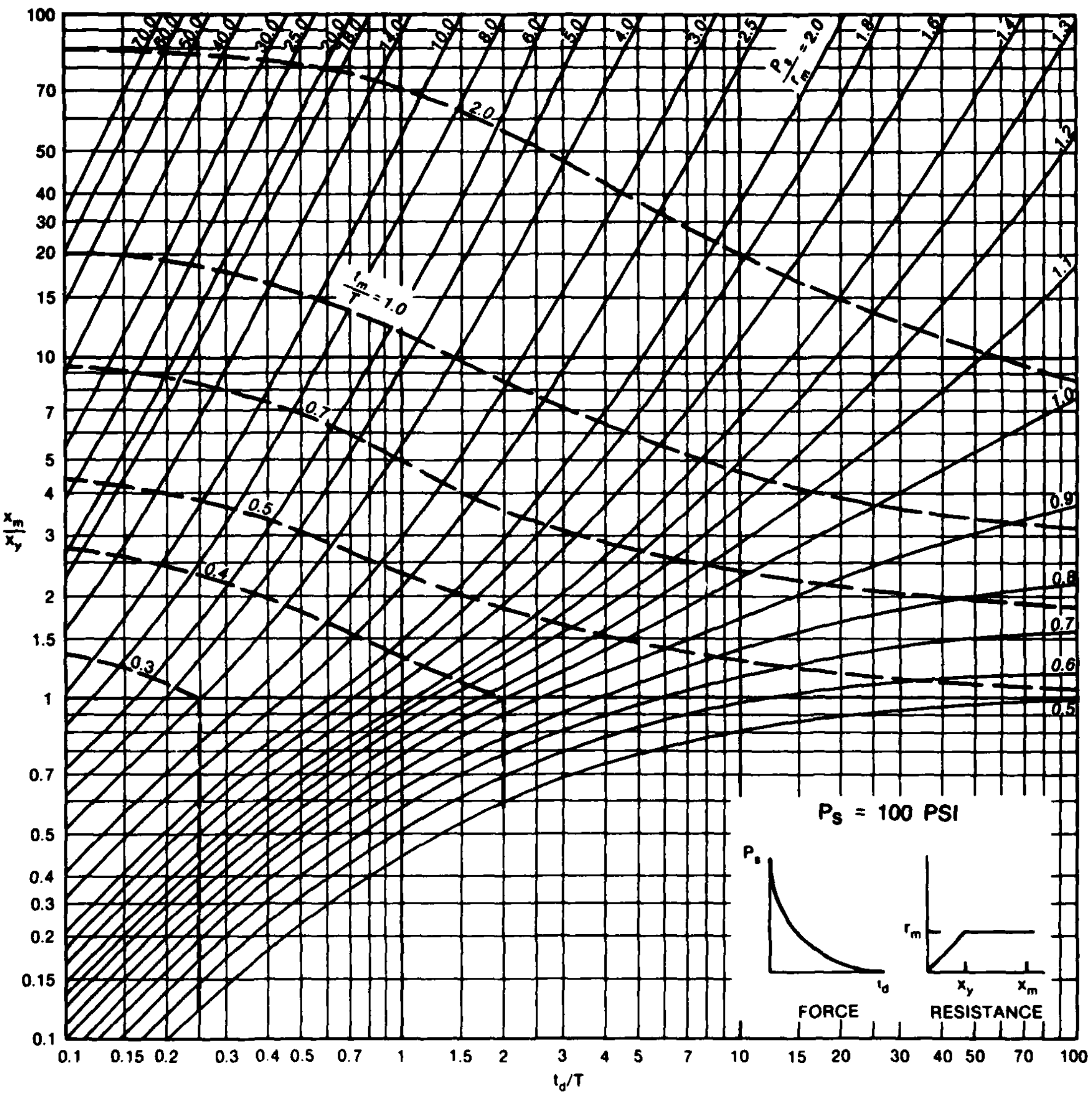


Figure 3.3. Maximum response of an elastic-plastic system subjected to a 100-psi Speicher-Brode pulse.

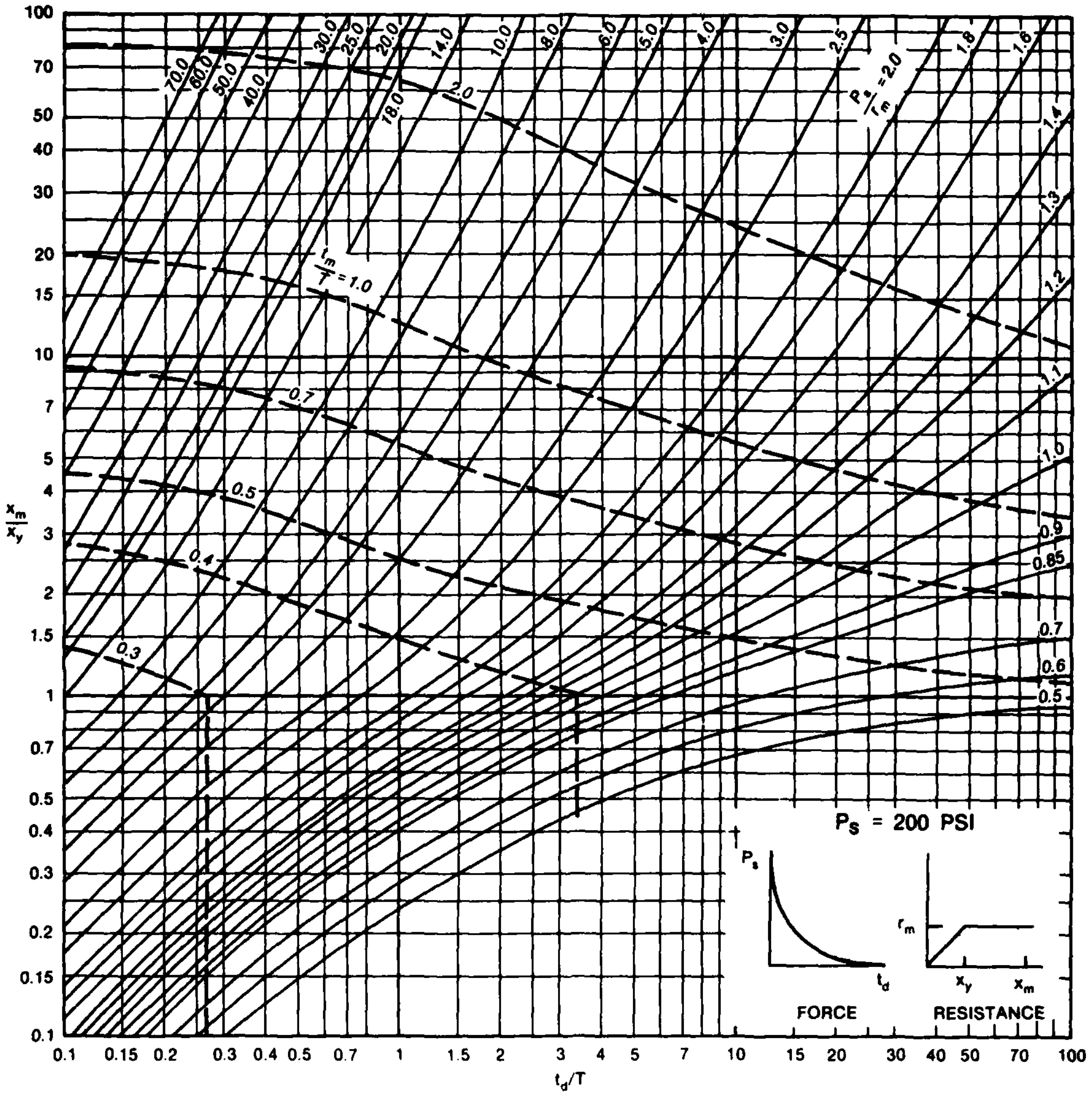


Figure 3.4. Maximum response of an elastic-plastic system subjected to a 200-psi Speicher-Brode pulse.

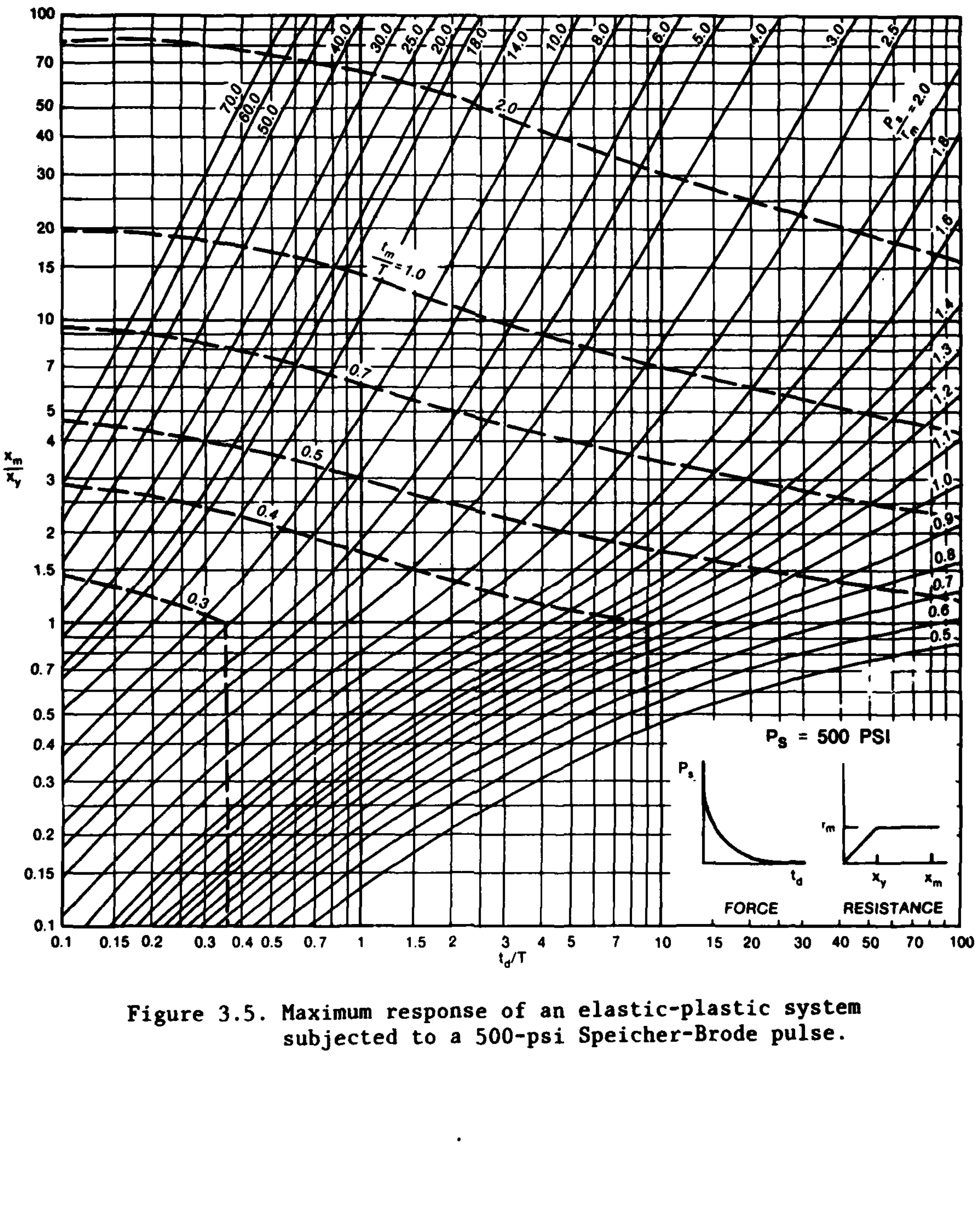


Figure 3.5. Maximum response of an elastic-plastic system subjected to a 500-psi Speicher-Brode pulse.

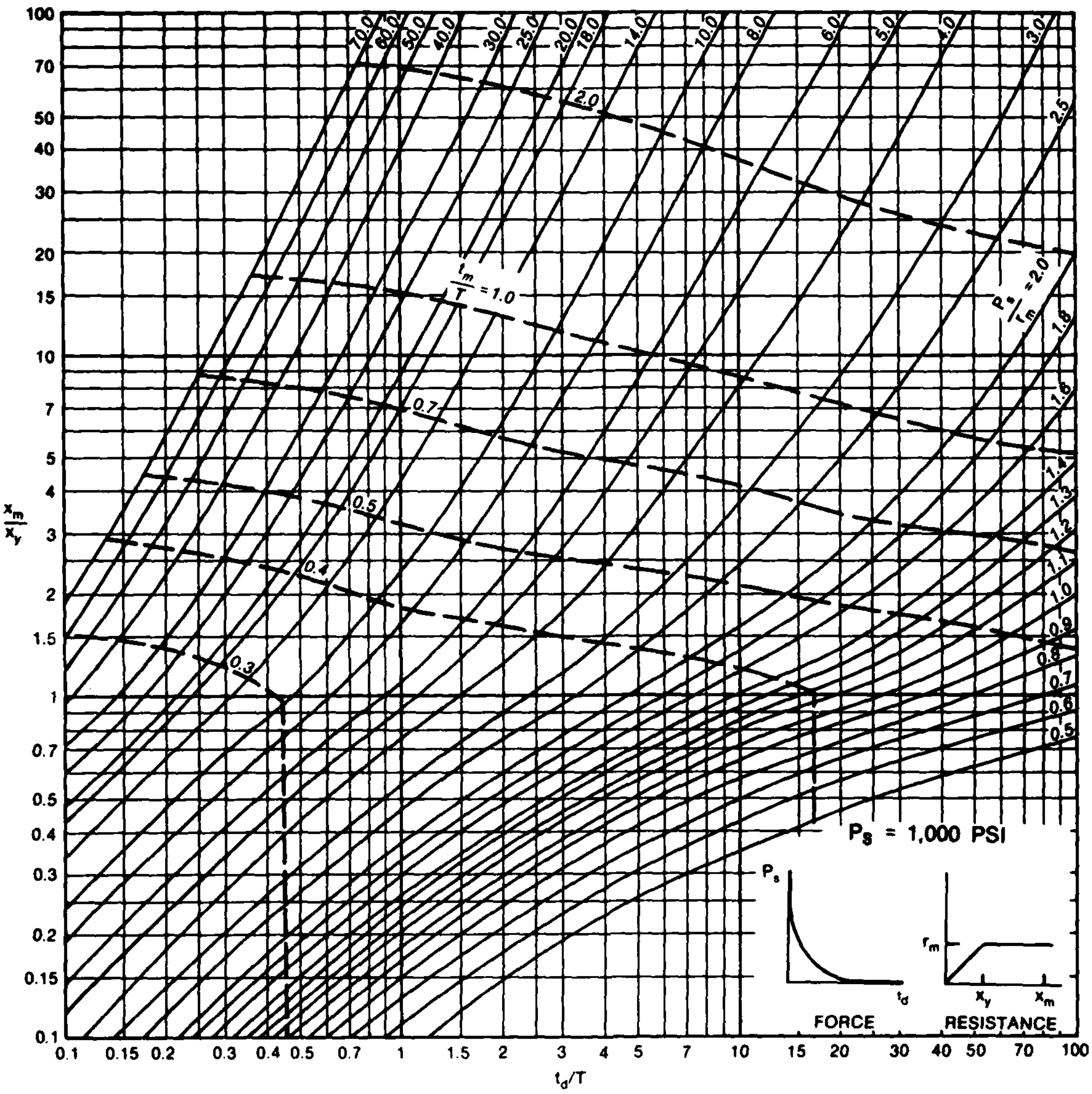


Figure 3.6. Maximum response of an elastic-plastic system subjected to a 1,000-psi Speicher-Brode pulse.

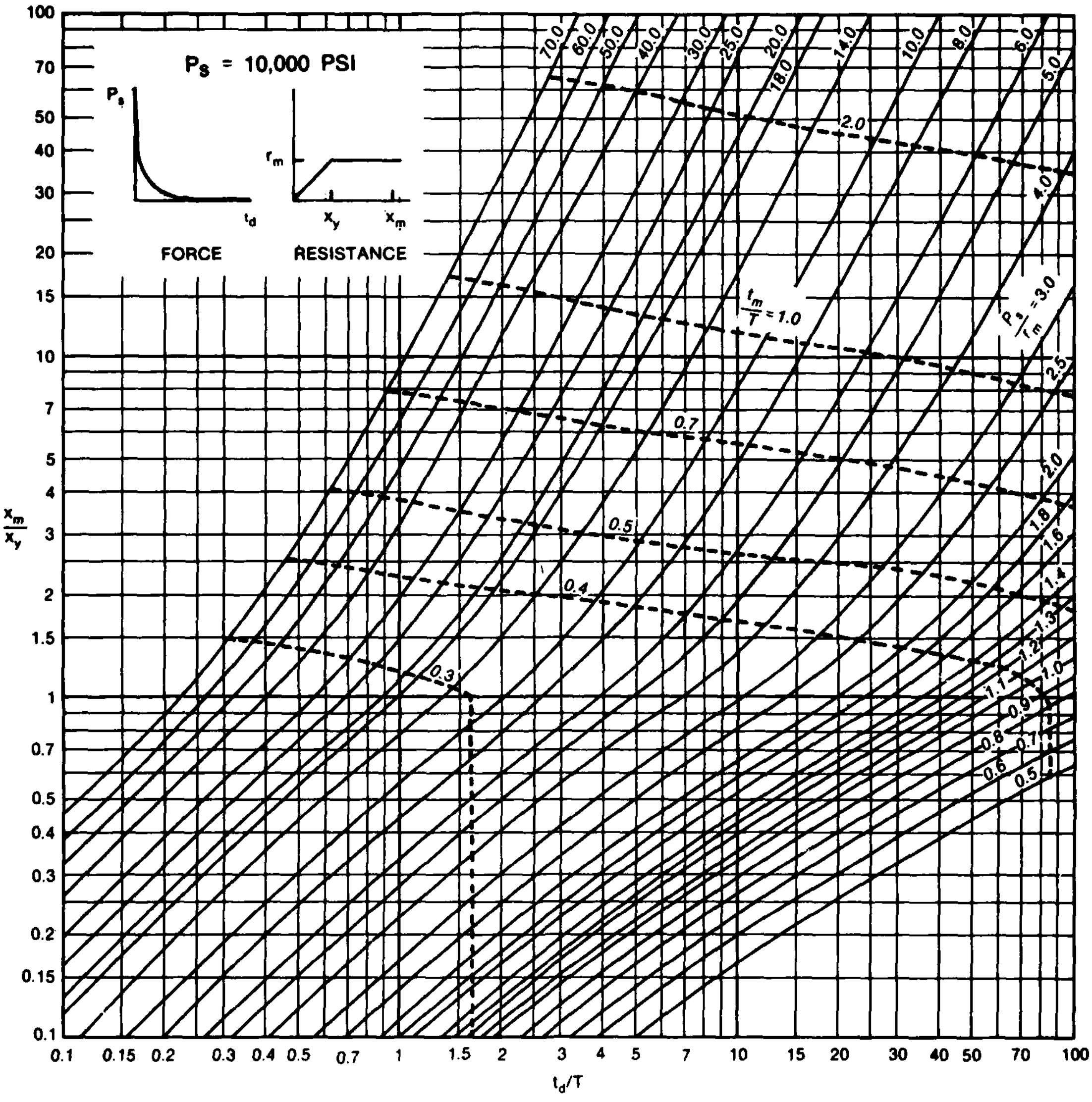


Figure 3.7. Maximum response of an elastic-plastic system subjected to a 10,000-psi Speicher-Brode pulse.

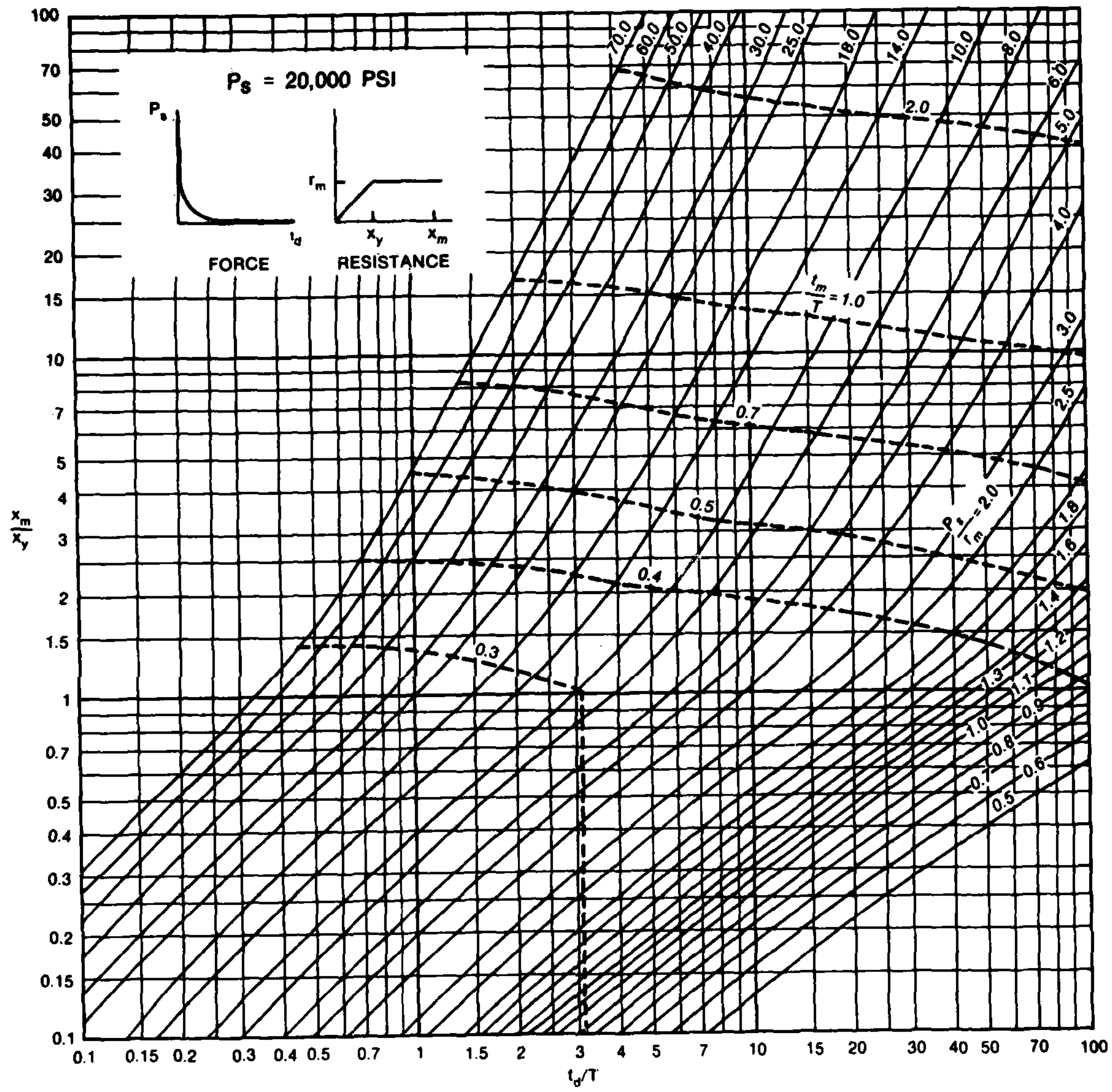


Figure 3.8. Maximum response of an elastic-plastic system subjected to a 20,000-psi Speicher-Brode pulse.

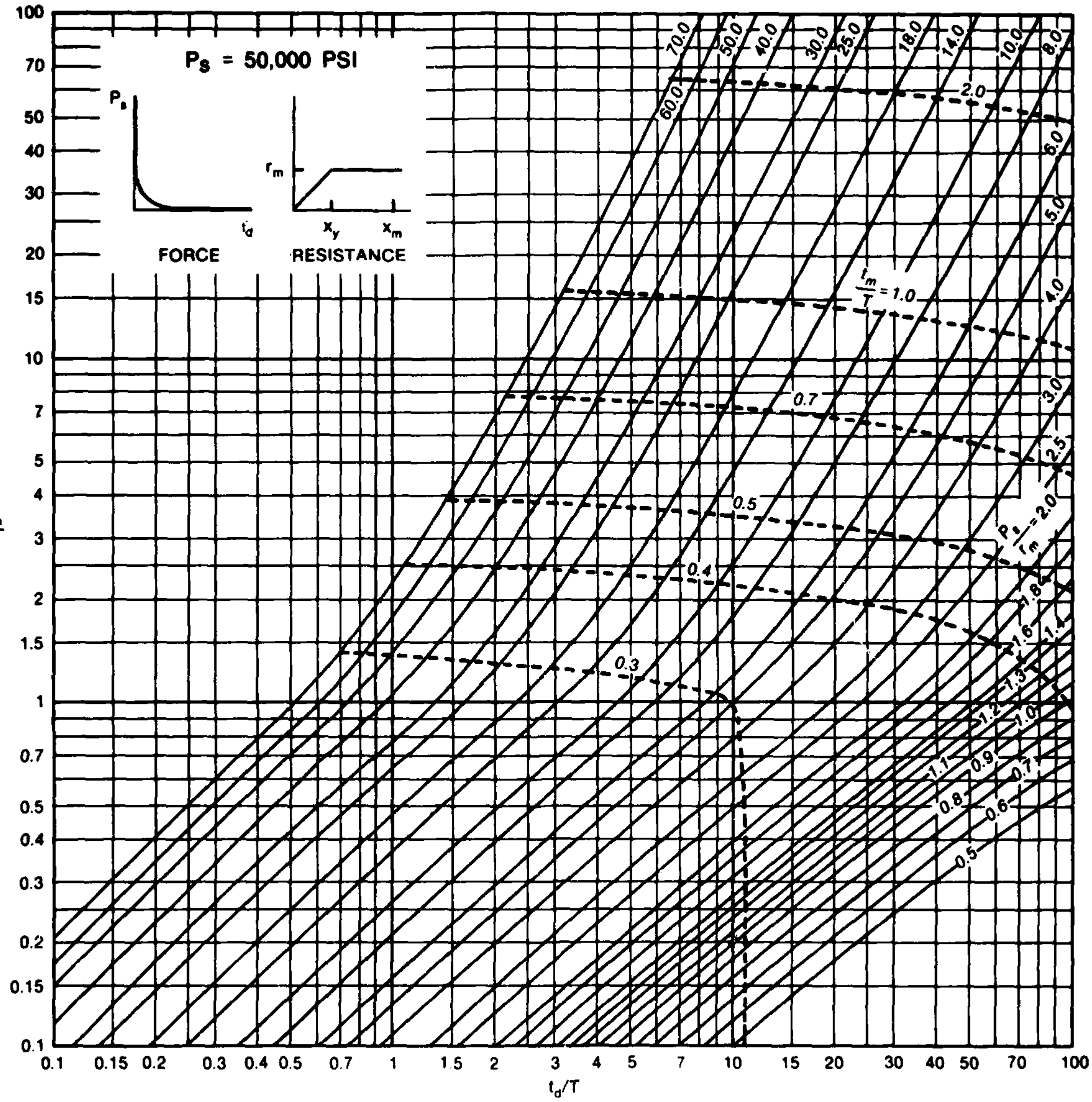


Figure 3.9. Maximum response of an elastic-plastic system subjected to a 50,000-psi Speicher-Brode pulse.

CHAPTER 4

CONCLUSIONS

The analysis and design of structures to resist loadings from nuclear weapons involve many parameters that are difficult to define. However, if those unknowns can be determined or at least approximated, then a straightforward solution can be readily obtained.

Two different ways for arriving at that solution for elastic-plastic systems with simulated nuclear loading definitions have been provided in this paper. The computer solution offers a quick and accurate way to investigate the effects of different parameters on the response. However, if a computer is not readily available or if a rough approximation to the numerically accurate solution is adequate, then the response charts are most beneficial. The response charts provide an efficient method for preliminary design calculations and for parametric investigations into such things as the effect of peak overpressure, weapon yield, structural resistance, and structural stiffness on the maximum response of a structure.

The charts do provide numerically accurate solutions for the specified overpressures, but interpolation to those overpressures not included on a chart does introduce some error into the analysis.

REFERENCES

1. American Society of Civil Engineers; "Design of Structures to Resist Nuclear Weapons Effects"; Manuals of Engineering Practice No. 42, 1961; New York.

2. J. M. Biggs; "Introduction to Structural Dynamics"; 1964; McGraw-Hill, New York.

3. S. J. Speicher and H. L. Brode; "Airblast Overpressure Analytical Expression for Burst Heights, Range and Time--Over an Ideal Surface"; PSR Note 385, November 1981; Pacific Sierra Research, Santa Monica, California.

4. N. M. Newmark; "A Method of Computation for Structural Dynamics"; Transactions, American Society of Civil Engineers, 1962, Vol. 127, Part 1, Pages 1406-1435; New York.

5. J. S. Hopkins; "Charts for Predicting Response of a Simple Spring-Mass System to Bilinear Blast Loads"; Report No. TN-1669, June 1983; Naval Civil Engineering Laboratory, Port Hueneme, California.

APPENDIX A

COMPUTER CODE LISTING

```
C***********************************************************************
C    PROGRAM FOR DETERMINING THE NORMALIZED RESPONSE OF AN SDOF        *
C    ELASTIC-PLASTIC MODEL SUBJECTED TO A SPEICHER-BRODE OR            *
C    A TRIANGULAR PULSE.  RESPONSES ARE NORMALIZED BY THE ELASTIC      *
C    DEFLECTION.         LES GUICE                    AUGUST 1983      *
C***********************************************************************
      IMPLICIT INTEGER*2(I-N,#)
      INTEGER*1 TITLE(72)
      DIMENSION P(250),RNU(501),RNUD(501),RNUDD(501)
      DATA TITLE/' ',' ','N','O','R','M','A','L','I','Z','E','D',
     1   ' ','R','E','S','P','O','N','S','E',' ','O','F',' ','A',
     2   ' ','S','D','O','F',' ','E','L','A','S','T','I','C','-',
     3   'P','L','A','S','T','I','C',' ','M','O','D','E','L',' ',
     4   ' ',' ',' ',' ',' ',' ',' ',' ',' ',' ',' ',' ',' ',' ',
     5   ' ',' ',' ',' '/
      NOPT=11
C
C   INITIALIZE ALL VALUES
C
      CALL GRSTRT(9)
      CALL BFACT(0,'USR:ANLOLY.LIB ')
1     LUO=6
      JOP=4
      IPASS=0
      NSTP=501
      NST=500
      NT=250
      NP=250
      W=1000.0
      PKT=100.0
      HOBK=0.0
      BT=0.16667
      TOL=1.0E-3
      TI1=0.01
      TI2=0.01
      TN=1.0
      RMX=1.0
10    CALL OVLINK('HELPOP ',LUO)
C
98    CALL OVLINK('GETOPT ',NOPT,JOP)
      GO TO(99999,1000,2000,10,3000,3000,4000,5000,6000,
     1      7000,8000),JOP
C
C   ANALYZE BY NEWMARK BETA METHOD
C
1000  CALL OVLINK('NEWMRK ',LUO,P,NT,NP,RNU,RNUD,RNUDD,NSTP,NST,
     1    TD,TN,TI1,TI2,PKT,RMX,BT,TOL,NNU,TINC)
      IPASS=2
      GO TO 98
C
C   DISPLAY DATA
C
2000  CALL OVLINK('DISPOP ',LUO,JOP,LFUNC,W,PKT,TD,TA,R,HOBK,TN,RMX,
```

```
      1   DPT,P,NT,NP,PKT,TITLE,BT,TI1,TI2,TOL,NP)
       IF(JOP.EQ.5)GO TO 7000
       GO TO 98
C
C    LOADING FUNCTION
C
3000   CALL OVLINK('LOADOP  ',LUO,JOP,LFUNC,W,PKT,TD,TA,R,HOBK,DPT,
      1     P,NT,NP)
       IPASS=1
       IF(JOP.EQ.5)GO TO 2000
       GO TO 98
C
C    NUMERICAL PARAMETERS
C
4000   CALL OVLINK('NUMOP  ',LUO,BT,TI1,TI2,TOL,NP)
       GO TO 98
C
C    OUTPUT DEVICE
C
5000   CALL OVLINK('OUTOP  ',LUO)
       GO TO 98
C
C    PLOT RESULTS
C
6000   CALL OVLINK('PLOTOP  ',LUO,TITLE,RNU,RNUD,RNUDD,NSTP,
      1     P,NT,NP,TD,NNU,TINC,IPASS)
       GO TO 98
C
C    SET VALUES FOR ANALYSIS
C
7000   CALL OVLINK('SETOP  ',LUO,TN,RMX)
       IF(JOP.EQ.5)GO TO 1000
       GO TO 98
C
C    TITLE
C
8000   CALL OVLINK('TITLOP  ',TITLE)
       GO TO 98
C
C    EXIT PROGRAM
C
99999 STOP
       END
```

```
      SUBROUTINE HELPOP(LUO)
      IMPLICIT INTEGER*2(I-N,#)
      CALL VTSCA(3)
      CALL HIBRN8(1)
10    WRITE(LUO,*)' '
      WRITE(LUO,*)' NORMALIZED RESPONSE OF AN SDOF ELASTIC-',
     1            'PLASTIC MODEL'
      WRITE(LUO,*)' '
      WRITE(LUO,*)' NOTE: DEFAULT UNITS ARE INCHES, POUNDS, AND SEC'
      WRITE(LUO,*)'       UNLESS OTHERWISE SPECIFIED.'
      WRITE(LUO,*)' '
      WRITE(LUO,*)' AVAILABLE OPTIONS:'
      WRITE(LUO,*)'   X - EXIT PROGRAM'
      WRITE(LUO,*)'   A - ANALYZE'
      WRITE(LUO,*)'   D - DISPLAY DATA'
      WRITE(LUO,*)'   H - HELP'
      WRITE(LUO,*)'   I - INITIAL PASS'
      WRITE(LUO,*)'   L - LOADING FUNCTION'
      WRITE(LUO,*)'   N - NUMERICAL PARAMETERS'
      WRITE(LUO,*)'   O - OUTPUT DEVICE'
      WRITE(LUO,*)'   P - PLOT'
      WRITE(LUO,*)'   S - SET VALUES FOR ANALYSIS'
      WRITE(LUO,*)'   T - TITLE'
      WRITE(LUO,*)' '
      RETURN
      END
```

```
      SUBROUTINE GETOPT(NOPT,JOP)
      IMPLICIT INTEGER*2(I-N,#)
      INTEGER*2 JOPT(11)
      DATA JOPT/'X ','A ','D ','H ','I ','L ','N ','O ','P ',
     1          'S ','T '/
      WRITE(6,*)' SELECT OPTION: (X,A,D,H,I,L,N,O,P,S,T)'
      CALL READC(IOPT,0,0)
      WRITE(6,*)' '
        DO 100 I=1,NOPT
100   IF(IOPT.EQ.JOPT(I))JOP=I
      RETURN
      END
```

```
C
      SUBROUTINE NEWMRK(LUO,P,NT,NP,RNU,RNUD,RNUDD,NSTP,NST,
     1     TD,TN,TI1,TI2,PKT,RMX,BT,TOL,NNU,TINC)
C
C    THIS SUBROUTINE IS USED TO INTEGRATE THE SDOF EQUATIONS
C    OF MOTION BY THE NEWMARK-BETA METHOD
C
      IMPLICIT INTEGER*2(I-N,#)
      DIMENSION P(NT),RNU(NSTP),RNUD(NSTP),RNUDD(NSTP)
      DATA INO/'N '/
      PI=3.1415927
      ANUM=4.0*PI**2.0
C    COMPUTE MAXIMUM RESPONSE FOR THE RATIO OF TD/TN AND PKT/RMX
      POR=PKT/RMX
C    DETERMINE TIME INCREMENT TO SATISFY CONVERGENCE AND
C    PROPER DESCRIPTION OF LOADING FUNCTION
      TI=TI1
      TINC=TI*TN
      IF(TD.GT.TN)GO TO 1000
      TI=TI2
      TINC=TI*TD
C    SET INITIAL VALUES OF NORMALIZED DISPLACEMENT(RNU),
C    VELOCITY(RNUD), AND COMPUTE INITIAL ACCELERATION(RNUDD)
1000  RNU(1)=0.0
      RNUMX=RNU(1)
      TMXT=0.0
      RNUD(1)=0.0
      RNUDD(1)=ANUM*POR
      TIDTN=TINC/TN
C    PERFORM THE INTEGRATION ITERATIVELY
C    BY ASSUMING AN ACCELERATION AND CHECKING CONVERGENCE
C
          DO 1500 J=1,NST
      JJ=J+1
      RNUDD(JJ)=RNUDD(J)
C    DETERMINE THE NORMALIZED PRESSURE THIS TIME STEP
      CALL PRESS(P,NT,NP,TD,JJ,TINC,SI,FT)
C    COMPUTE NORMALIZED DISPLACEMENT AND VELOCITY
1100  RNU(JJ)=RNU(J)+TIDTN*RNUD(J)+TIDTN*TIDTN*(0.5-BT)*RNUDD(J)+
     1    TIDTN*TIDTN*BT*RNUDD(JJ)
      RNUD(JJ)=RNUD(J)+0.5*TIDTN*(RNUDD(J)+RNUDD(JJ))
      TNU=RNU(JJ)
C    DETERMINE IF RESPONSE IS IN PLASTIC RANGE
      IF(RNU(JJ).GT.1.0)TNU=1.0
C    CHECK CONVERGENCE
      RNUCK=ANUM*(FT*POR-TNU)
      IF(ABS(RNUCK-RNUDD(JJ)).LE.TOL)GO TO 1200
      IF(RNUCK.EQ.RNUDD(J))GO TO 1200
C    NOT CONVERGED, ASSUME NEW ACCELERATION
      RNUDD(JJ)=RNUCK
      GO TO 1100
C    CONVERGED, DETERMINE IF A MAXIMUM
```

```
1200  IF(RNU(JJ).LE.RNU(J))GO TO 2000
      RNUMX=RNU(JJ)
      TM=SI
      FM=FT
      NNU=JJ
1500  CONTINUE
      WRITE(LUO,*)' CAUTION: SOLUTION NOT CONVERGED!'
C
C   DISPLACEMENT IS DECREASING, MAX. AT PREVIOUS STEP
C   WRITE OUT RESULTS OF ANALYSIS
2000  WRITE(LUO,*)' '
      WRITE(LUO,*)'     MAXIMUM DUCTILITY =',RNUMX
      WRITE(LUO,*)'     OCCURS AT TIME =',TM
      WRITE(LUO,*)'     NORMALIZED PRESSURE AT THIS TIME =',FM
      WRITE(LUO,*)' '
      WRITE(LUO,*)'     NATURAL PERIOD =',TN
      WRITE(LUO,*)'     LOAD DURATION =',TD
      WRITE(LUO,*)'     TIME INCREMENT =',TINC
      WRITE(LUO,*)' '
      WRITE(6,*)' COMPLETE HISTORY? (Y/N):'
      CALL READC(IANS,0,0)
      WRITE(6,*)' '
      IF(IANS.EQ.INO)RETURN
      WRITE(LUO,*)' '
      WRITE(LUO,*)'     NOTE: RESPONSES ARE NORMALIZED:'
      WRITE(LUO,*)' '
      WRITE(LUO,*)'     TIME          DISP          VEL          ACC'
      T=0.0-TINC
          DO 2500 I=1,JJ
      T=T+TINC
2500  WRITE(LUO,2510)T,RNU(I),RNUD(I),RNUDD(I)
2510  FORMAT(2(2X,F10.5),2(2X,F10.5))
      WRITE(LUO,*)' '
      RETURN
      END
```

```
C
      SUBROUTINE PRESS(P,NT,NP,TD,JJ,TINC,SI,FT)
C
C    SUB FOR COMPUTING NORMALIZED PRESSURE AT A GIVEN TIME STEP
C
      IMPLICIT INTEGER*2(I-N,#)
      DIMENSION P(NT)
C
C    SI = REAL TIME FOR THIS STEP
C    SID = NORMALIZED TIME AT END OF DURATION
C    FT = NORMALIZED PRESSURE AT GIVEN TIME
C    TINC = TIME INCREMENT
C    DELTT = TIME INCREMENT BASED ON NUMBER OF PRESSURE STATIONS
C
      SI=TINC*FLOAT(JJ-1)
C    IF TIME IS BEYOND POSITIVE DURATION, SET PRESSURE = 0
      IF(SI.LT.TD)GO TO 500
      FT=0.0
      RETURN
C    FIND PRESSURE STATION ON EITHER SIDE OF GIVEN TIME
500   DELTT=TD/FLOAT(NP-1)
      IST1=INT2(SI/DELTT)+1
      ST1=FLOAT(IST1)
      ST2=ST1+1.0
      IST2=IST1+1
      P11=P(IST1)
      P12=P(IST2)
      TST1=(ST1-1.0)*DELTT
      TST2=TST1+DELTT
C    INTERPOLATE TO FIND PRESSURE THIS TIME STEP
      FT=(P11-P12)*(SI-TST2)/(TST1-TST2)+P12
      RETURN
      END
```

```
      SUBROUTINE DISPOP(LUO,JOP,LFUNC,W,PKT,TD,TA,R,HOBK,TN,RMX,
     1   DPT,P,NT,NP,PKT,TITLE,BT,TI1,TI2,TOL,NP)
      IMPLICIT INTEGER*2(I-N,$)
      INTEGER*2 IFU(3)
      INTEGER*1 TITLE(72)
      DIMENSION P(NT)
      DATA INO/'N '/,IFU/'S ','T ','X '/
C
C   DISPLAY DATA
C
      WRITE(LUO,*)' '
      WRITE(LUO,2010)(TITLE(I),I=1,72)
2010  FORMAT(1X,72A1)
      WRITE(LUO,*)' '
      WRITE(LUO,*)'     NUMERICAL PARAMETERS:'
      WRITE(LUO,*)'      BETA = ',BT
      WRITE(LUO,*)'      INTEGRATION INTERVAL =',TI1,' OF PERIOD'
      WRITE(LUO,*)'      INTEGRATION INTERVAL =',TI2,' OF DURATION'
      WRITE(LUO,*)'      TOLERANCE =',TOL
      WRITE(LUO,*)'      NUMBER OF PRESSURE STATIONS =',NP
      WRITE(LUO,*)' '
      WRITE(LUO,*)'     LOAD DESCRIPTION:'
      IF(LFUNC.EQ.IFU(1))GO TO 2050
      IF(LFUNC.EQ.IFU(2))GO TO 2100
      GO TO 2200
2050  WRITE(LUO,*)'      WEAPON (KT)=',W
2100  WRITE(LUO,*)'      PEAK OVERPRESSURE =',PKT
      WRITE(LUO,*)'      POSITIVE PHASE DURATION =',TD
      IF(LFUNC.EQ.IFU(2))GO TO 2200
      WRITE(LUO,*)'      TIME OF ARRIVAL =',TA
      WRITE(LUO,*)'      RANGE (KFEET) =',R
      WRITE(LUO,*)'      HEIGHT OF BURST (KFEET) =',HOBK
      IF(JOP.EQ.5)GO TO 2250
2200  WRITE(LUO,*)' '
      WRITE(LUO,*)'     STRUCTURE DESCRIPTION:'
      WRITE(LUO,*)'      NATURAL PERIOD =',TN
      FREQ=1.0/TN
      WRITE(LUO,*)'      FREQUENCY =',FREQ
      WRITE(LUO,*)'      PEAK RESISTANCE =',RMX
2250  WRITE(LUO,*)' '
      WRITE(6,*)' PRESSURE-TIME HISTORY? (Y/N)'
      CALL READC(IANS,0,0)
      WRITE(6,*)' '
      IF(IANS.EQ.INO)RETURN
      T=0.0-DPT
      WRITE(LUO,*)' '
      WRITE(LUO,*)'      TIME     PRESSURE      NORMALIZED'
      WRITE(LUO,*)' '
         DO 2300 I=1,NP
      PTPKT=P(I)*PKT
      T=T+DPT
2300  WRITE(LUO,2310)T,PTPKT,P(I)
2310  FORMAT(3(2X,F10.4))
      RETURN
      END
```

```
      SUBROUTINE LOADOP(LUO,JOP,LFUNC,W,PKT,TD,TA,R,HOBK,DPT,
     1    P,NT,NP)
      IMPLICIT INTEGER*2(I-N,#)
      INTEGER*2 IFU(3)
      DIMENSION P(NT)
      DATA IFU/'S ','T ','X '/
C
C   LOADING FUNCTION
C
      WRITE(6,*)' SELECT SPEICHER-BRODE, TRIANGULAR,',
     1              ' OR EXIT: (S,T,X)'
      CALL READC(LFUNC,0,0)
      WRITE(6,*)' '
          DO 3100 I=1,3
      IF(LFUNC.EQ.IFU(I))IFUOP=I
3100  CONTINUE
      GO TO(3200,3300,3500),IFUOP
3200  WRITE(6,*)' ENTER WEAPON(KT):'
      READ(5,*)W
      WRITE(6,*)' ENTER PEAK OVERPRESSURE:'
      READ(5,*)PKT
      WRITE(6,*)' ENTER HEIGHT OF BURST(KFEET):'
      READ(5,*)HOBK
      CALL BRODEP(P,TD,DPT,W,PKT,NT,NP,HOBK,R,TA)
      TD=TD/1000.0
      TA=TA/1000.0
      DPT=DPT/1000.0
      GO TO 3400
3300  WRITE(6,*)' ENTER PEAK OVERPRESSURE:'
      READ(5,*)PKT
      WRITE(6,*)' ENTER DURATION:'
      READ(5,*)TD
      CALL BIGGS(P,NT,NP,TD,DPT,PKT)
3400  READ(5,3410)IDUMMY
3410  FORMAT(A2)
3500  RETURN
      END
```

```
C$TITLE  FILED IN BRODEP
      SUBROUTINE BRODEP(PEST, DP, DT, W, P, NPTS,NP,HOBK,R,TA)
      IMPLICIT INTEGER *2(I-N,$)
      DOUBLE PRECISION XP,YP,DPP
C
C
      DIMENSION PEST(NPTS)
C
C  TA ARRIVAL TIME (MSEC)
C  RANGE IN KFEET
C
C  DP POSITIVE PHASE DUR. (MSEC)
C  DT INCREMENT BETWEEN PRESSURE STATIONS
      IONE = 0
      W13 = W**(1./3.)
      YP = HOBK/W13
      DTT = DT/W13
C
      XP = ((1.58 * 2. * W / P) ** (1. / 3.))/W13
   10 CALL PT(XP,YP,DTT,PEST(1),DPP,IONE,NPTS,NP,TA)
      IF (ABS(PEST(1)/P-1.) .LE. 5.E - 5) GO TO 20
      CALL PT(XP*1.00001,YP,DTT,EST,DPP,IONE,NPTS,NP,TA)
      XP = XP + (PEST(1) - P) * 0.00001 * XP / (PEST(1) - EST)
      GO TO 10
   20 R = XP*W13
      IONE=1
      CALL PT(XP,YP,DTT,PEST,DPP,IONE,NPTS,NP,TA)
      DP = DPP*W13
      TA = TA*W13
C   NOTE - REDEFINITION OF DT BELOW - LKG  7/83
      DT=DTT*W13
C
C
      RETURN
      END
```

```
C$TITLE       FILED IN PT
      SUBROUTINE PT(X,Y,DTT,P,DP,IP,NPT,NP,TAS)
C
C  THIS IS AN IMPLEMENTATION OF THE SPEICHER AND BRODE
C  OCT 1981 P(T,X,Y) NUC, HISTORY
C  REF.   PSR NOTE 385 WITH MOD FOR P ABOVE 10000 PSI
C  WALKER NOV.17,1982
C  INPUT PARAMETERS
C  X = RANGE (KFT/W**1/3)
C  Y = HOB (KRT/W**1/3)
C  T = TIME AFTER TIME OF ARRIVAL (MSEC)
C  IP = 0 FOR PEAK PRESSURE ONLY
C     DTT = TIME STEP SCALED (MSEC/W**1/3)
C
C  OUTPUT PARAMETERS
C
C  P = PRESSURE*TT(PSI)
C  DP = POSITIVE PHASE DURATION (MSEC)
C  ***NOTE T IS CHANGE IN THIS ROUTINE.
       IMPLICIT INTEGER*2 (I-N,$)
        IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      REAL P, DTT, TAS
      DIMENSION P(NPT)
C
       XLEAST=1.E-4
       YLEAST=1.E-4
       ZLEAST=1.E-4
       ZMOST=100.
       IF(X.LT.XLEAST) X=XLEAST
       IF(Y.LT.YLEAST) Y=YLEAST
       R=DSQRT(X*X+Y*Y)
       Z=Y/X
       IF(Z.LT.ZLEAST) Z=ZLEAST
       IF(Z.GT.ZMOST) Z=ZMOST
       CALL PPEAK(X,Y,R,Z,DELTAP)
      P(1) = DELTAP
      IF(IP.EQ.0) RETURN
       XM=170.*Y/(1.+337.*Y**.25)+.914*Y**2.5
       U=(.543-21.8*R+386.*R*R+2383.*R*R*R)*R**8
       UD=2.99E-14-(1.91E-10*R*R)+(1.032E-6*R**4)-(4.43E-6*R**6)+
     &    (1.028+(2.087*R)+(2.69*R*R))*R**8
       U=U/UD
       TA=U
       IF(X.LT.XM)GO TO 200
      W=(1.086-34.605*R+486.3*R*R+2383.*R*R*R)*R**8
      WD=3.0137E-13-(1.2128E-9*R*R)+(4.128E-6*R**4)-(1.116E-5*R**6)+
     &   (1.632+2.629*R+2.69*R*R)*R**8
      W=W/WD
       TA=(U*XM/X)+(W*(1.-XM/X))
  200  CONTINUE
        S = 1.-1.1E10*(Y**7)/(1.+1.1E10*Y**7)-(2.441E-8*Y*Y/
     &    (1.+9.E10*Y**7))*(1./(4.41E-11+X**10))
        F = (.01477*(TA**.75)/(1.+.005836*TA)+7.402E-5*(TA**2.5)/
     &      (1.+1.429E-8*TA**4.75)-.216)*S + .7076-3.077E-5*TA*TA*TA/
     &      (1.+4.367E-5*TA*TA*TA)
        G = 10.+(77.58-64.99*(TA**.125)/(1.+.04348*DSQRT(TA)))*S
```

```
      H = 2.753+.05601*TA/(1.+1.473E-9*TA**5)+(.01769*TA/
     &     (1.+3.207E-10*TA**4.25)-.03209*(TA**1.25)/(1.+9.914E-8*
     &     TA**4)-1.6)*S
      DP =((1640700.+24629.*TA+416.15*TA*TA)/(10880.+619.76*TA+TA*TA))*
     &       (.4+.001204*(TA**1.5)/(1.+.001559*TA**1.5)+(.0426+.5486*
     &   (TA**.25)/(1.+.00357*TA**1.5))*S)
C***
C  NOTE MODIFICATION BELOW -
C  COMPUTE TIME STEP BY DIVIDING THE POSITIVE PHASE DURATION
C  BY THE NUMBER OF DESIRED TIME STEPS
C***
      DTT=DP/FLOAT(NP-1)
      DO 500 I = 1,NP
      T = TA+(DTT*(I-1))
       B = (F*(TA/T)**G+(1.-F)*(TA/T)**H)*(1.-(T-TA)/DP)
       IF (X.LT.XM .OR. Y.GT.0.38) GO TO 1000
       XE = 3.039*Y/(1.+6.7*Y)
       E = DABS((X-XM)/(XE-XM))
       IF (E.GT.50.)E=50.
       D = .23+583000.*Y*Y/(26667.+1000000.*Y*Y)+.27*E+(.5-583000.*Y*Y/
     &     (26667.+1000000.*Y*Y))*E**5
       A = (D-1.)*(1.-(E**20)/(1.+E**20))
       DT = 474.2*Y*(X-XM)**1.25
       IF(DT.LT.1.E-4) DT=1.E-4
       GA = (T-TA)/DT
       IF(GA.GT.400.) GA=400.
       V = 1.+(3.28E11*(Y**6)/(1.+1.5E12*Y**6.75))*(GA*GA*GA/
     &     (6.13+GA*GA*GA))*(1./(1.+9.23*E*E))
       C= ((1.04-240.9*(X**4)/(1.+231.7*X**4))*(GA**7)/((1.+.923*
     &     (GA)**8.5)*(1+A)))*(1.-((T-TA)/DP)**8)*2.3E13*(Y**9)/(1.+
     &     2.3E13*Y**9)
       P(I) = DELTAP*(1.+A)*(B*V+C)
       GO TO 495
 1000   CONTINUE
       P(I) = DELTAP*B
C***
C  NOTE MODIFICATION BELOW -
C  NORMALIZE ALL PRESSURES BY DIVIDING BY PEAK PRESSURE
C***
495   P(I)=P(I)/DELTAP
500   CONTINUE
      TAS = TA
      RETURN
      END
```

```
C$TITLE      FILED IN PPEAK
      SUBROUTINE PPEAK(X,Y,R,Z,DELTAP)
C
C   SUB FOR PEAK OVERPRESSURE BY SPEICHER AND BRODE,SEPT.1980
C   MOD BY WALKER FROM MOD BY SPIECHER AND BRODE MARCH 1981
C   RANGE TO 0.1 PSI
C
C   INPUT PARAMETERS
C   X=RANGE (KFT/KT**1/3)
C   Y=HOB   (KFT/KT**1/3)
C   R=SQRT(X**2+Y**2)   (KFT/KT**1/3)
C   Z=Y/X
C    OUTPUT
C    DELTAP=PEAK PRESSURE  (PSI)
C
      IMPLICIT INTEGER*2 (I-N,$)
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
C
      A = 1.22-(3.908*Z*Z)/(1.+810.2*Z**5)
      B = 2.321+((Z**18)/(1.+1.113*Z**18))*6.195-(.03831*Z**17)/
     &    (1.+.02415*Z**17)+.6692/(1.+4164.*Z**8)
      C = 4.153-(1.149*Z**18)/(1.+1.641*Z**18)-1.1/(1.+2.771*Z**2.5)
      D = -4.166+(25.76*Z**1.75)/(1.+1.382*Z**18)+8.257*Z/(1.+3.219*Z)
      E = 1.-(.004642*Z**18)/(1.+.003886*Z**18)
      F = .6096+(2.879*Z**9.25)/(1.+2.359*Z**14.5)-17.15*Z*Z/
     &    (1.+71.66*Z*Z*Z)
      G = 1.83+5.361*Z*Z/(1.+.3139*Z**6)
      H =-(64.67*Z**5+.2905)/(1.+441.5*Z**5)-1.389*Z/(1.+49.03*Z**5)+
     &   (8.808*Z**1.5)/(1.+154.5*Z**3.5)+(.0014*R*R/(1.-.158*R+.0486*
     &    R**1.5 +.00128*R*R))*(1./(1.+2.*Y))
C
      DELTAP=10.47/(R**A)+B/(R**C)+D*E/(1.+F*R**G)+H
      RETURN
      END
```

```
      SUBROUTINE BIGGS(P,NT,NP,TD,DTT,PKT)
C
C    GENERATE NONDIMENSIONALIZED PRESSURES FOR TRIANGULAR PULSE
      IMPLICIT INTEGER*2(I-N,$)
      DIMENSION P(NT)
      DTT=TD/FLOAT(NP-1)
      P(1)=PKT/PKT
          DO 500 I=1,NT
500   P(I)=P(1)-(I-1)*DTT/TD
      RETURN
      END
```

```
      SUBROUTINE NUMOP(LUO,BT,TI1,TI2,TOL,NP)
C
C   NUMERICAL PARAMETERS
C
      IMPLICIT INTEGER*2(I-N,#)
      INTEGER*2 NUOP(5)
      DATA NUOP/'B ','I ','T ','N ','X '/
      NOP=5
      NUMOPT=5
      WRITE(6,*)' '
      WRITE(6,*)' SELECT NUMERICAL PARAMETER: (B,I,T,N,X)'
      WRITE(6,*)'      B - BETA'
      WRITE(6,*)'      I - INTEGRATION INCREMENT'
      WRITE(6,*)'      T - TOLERANCE'
      WRITE(6,*)'      N - NUMBER OF PRESSURE STATIONS'
      WRITE(6,*)'      X - EXIT'
      WRITE(6,*)' '
      CALL READC(IOPT,0,0)
      WRITE(6,*)' '
      NUMOPT=5
          DO 10 I=1,NOP
10    IF(IOPT.EQ.NUOP(I))NUMOPT=I
      GO TO(100,200,300,400,500),NUMOPT
C
100   WRITE(6,*)' ENTER BETA: (LINEAR ACCELERATION = 0.16667)'
      READ(5,*)BT
      GO TO 498
200   WRITE(6,*)' ENTER TIME INCREMENT/PERIOD: (TI/TN = 0.01)'
      READ(5,*)TI1
      WRITE(6,*)' ENTER TIME INCREMENT/LOAD DURATION: (TI/TD = 0.01)
      READ(5,*)TI2
      GO TO 498
300   WRITE(6,*)' ENTER CONVERGENCE TOLERANCE: (TOL. = 1E-3)'
      READ(5,*)TOL
      GO TO 498
400   WRITE(6,*)' ENTER NUMBER OF PRESSURE STATIONS:(MAX. = 250)'
      WRITE(6,*)'      CAUTION: MUST COMPUTE NEW LOAD FUNCTION!'
      READ(5,*)NP
498   READ(5,499)IDUMMY
499   FORMAT(A2)
500   RETURN
      END
```

```
      SUBROUTINE OUTOP(LUO)
      IMPLICIT INTEGER*2(I-N,$)
      INTEGER*2 JDEV(2)
      DIMENSION P(250),RNU(1001),RNUD(1001),RNUDD(1001)
      DATA JDEV/'T ','P '/
C
C   OUTPUT DEVICE
C
5000  WRITE(6,*)' SELECT TERMINAL OR PRINTER: (T,P)'
      CALL READC(IDEV,0,0)
      WRITE(6,*)' '
      IF(IDEV.EQ.JDEV(1))LUO=6
      IF(IDEV.EQ.JDEV(2))GO TO 5100
      RETURN
5100  LUO=8
      CALL ASSIGN('LP: ',LUO,ISTAT)
      RETURN
      END
```

```
      SUBROUTINE PLOTOP(LUO,TITLE,RNU,RNUD,RNUDD,NSTP,
     1    P,NT,NP,TD,NNU,TINC,IPASS)
      IMPLICIT INTEGER*2(I-N,*)
      INTEGER*1 TITLE(72)
      INTEGER*2 JPLT(5)
      DIMENSION P(NT),RNU(NSTP),RNUD(NSTP),RNUDD(NSTP)
      DATA JPLT/'D ','V ','A ','L ','X '/
C
C   PLOT RESULTS
C
      WRITE(6,*)' SELECT PLOT: (D,V,A,L,X)'
      CALL READC(IPLT,0,0)
      WRITE(6,*)' '
      JPL=5
          DO 6100 I=1,4
6100  IF(IPLT.EQ.JPLT(I))JPL=I
      IF(JPL.EQ.5)RETURN
      IF(IPASS.LT.1)GO TO 6200
      IF(IPASS.LT.2.AND.JPL.LE.3)GO TO 6200
      DT=TD/(FLOAT(NP-1))*1000.0
      TINCP=TINC*1000.0
      CALL PLOT(JPL,NSTP,NT,NP,RNU,RNUD,RNUDD,P,TITLE,
     1      NNU,TINCP,DT)
      RETURN
6200  WRITE(6,*)' ERROR: DATA FOR PLOT NOT AVAILABLE!'
      RETURN
      END
```

```
      SUBROUTINE PLOT(JPL,NSTP,NT,NP,RNU,RNUD,RNUDD,P,TITLE,
     1       NNU,TINC,DELT)
C   SUBROUTINE FOR PLOTTING RESPONSES
      IMPLICIT INTEGER*2(I-N,$)
      INTEGER*1 TITLE(72)
      DIMENSION P(NT),RNU(NSTP),RNUD(NSTP),RNUDD(NSTP)
      DATA K11/11/, K22/22/, K30/30/, K36/36/, TZ/0./
C
      IF(JPL.LT.4)CALL TITLX('TIME (MSEC)',K11)
      CALL NEXTPG
C   WRITE TITLE TO PLOT
      CALL VTSCA(5)
      CALL HIBRN8(1)
      WRITE(6,90)TITLE
90    FORMAT(10X,72A1)
      CALL VTSCA(3)
      CALL OIBRN8(1)
C
      GO TO (100,20),300,400),JPL
100   CALL TITLY1('NORMALIZED DISPLACEMENT (D/XY)',K30)
      CALL QPLOTD(TZ,TINC,RNU,NNU)
      CALL NEXTPG
      RETURN
200   CALL TITLY1('NORMALIZED VELO CITY (V*T/XY)  ',K30)
      CALL QPLOTD(TZ,TINC,RNUD,NNU)
      CALL NEXTPG
      RETURN
300   CALL TITLY1('NORMALIZED ACCELERATION (A*T*T/XY)  ',K36)
      CALL QPLOTD(TZ,TINC,RNUDD,NNU)
      CALL NEXTPG
      RETURN
400   CALL TITLX('TIME (MSEC)',K11)
      CALL TITLY1('NORMALIZED PRESSURE   ',K22)
      CALL QPLOTD(TZ,DELT,P,NP)
      CALL NEXTPG
      RETURN
      END
```

```
      SUBROUTINE SETOP(LUO,TN,RMX)
      IMPLICIT INTEGER*2(I-N,#)
C
C    SET VALUES FOR ANALYSIS
C
      WRITE(6,*)' ENTER NATURAL PERIOD:'
      READ(5,*)TN
      WRITE(6,*)' ENTER PEAK RESISTANCE:'
      READ(5,*)RMX
      READ(5,10)IDUMMY
10    FORMAT(A2)
      RETURN
      END
```

```
      SUBROUTINE TITLOP(TITLE)
      IMPLICIT INTEGER*2(I-N,#)
      INTEGER*1 TITLE(72)
      WRITE(6,*)' ENTER NEW TITLE: (72 CHAR. MAX.)'
      READ(5,10)(TITLE(I),I=1,72)
10    FORMAT(72A1)
      RETURN
      END
```

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APPENDIX B

EXAMPLE COMPUTER SOLUTIONS

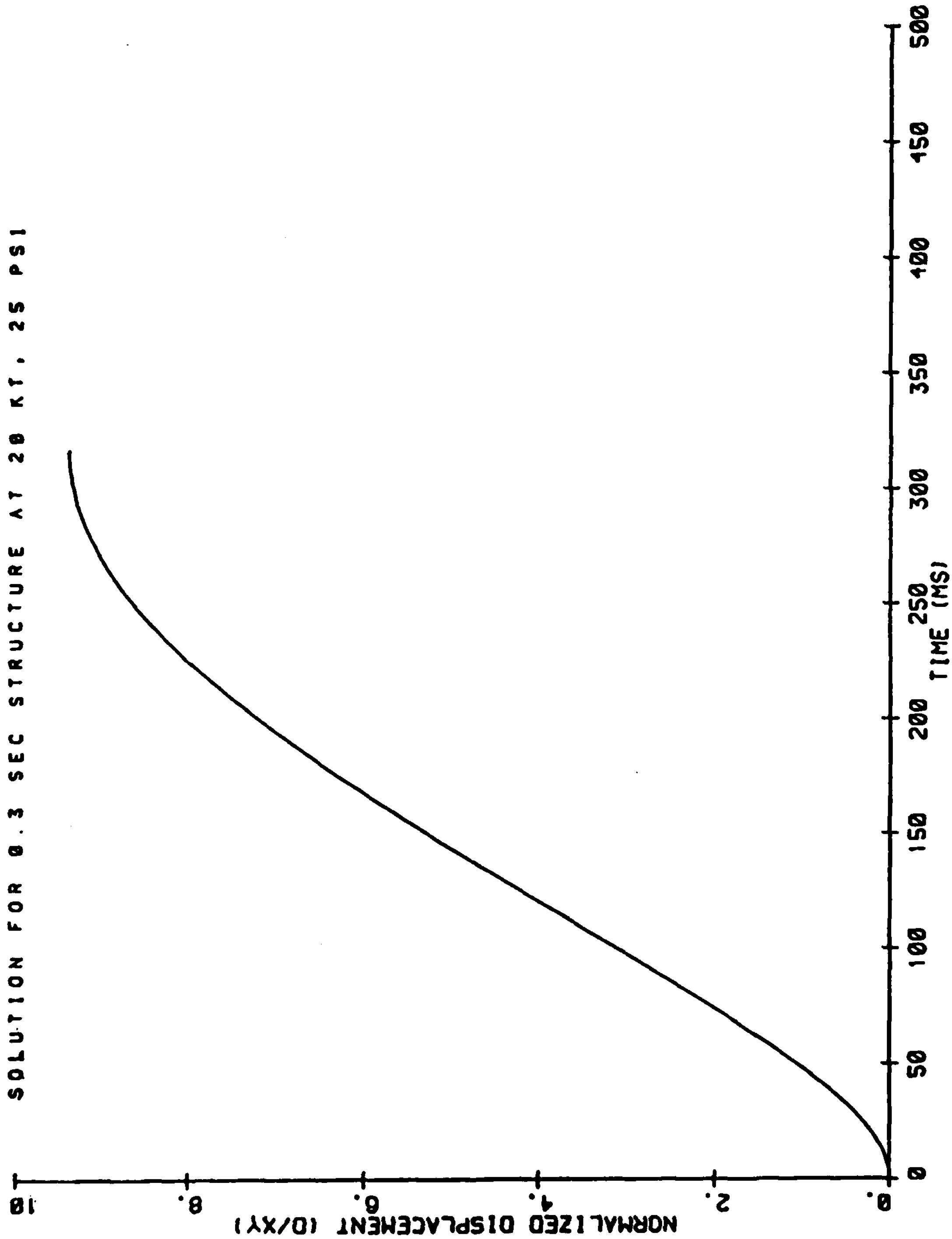
```
#RUN ANAL/ANAL.EXQ

 NORMALIZED RESPONSE OF AN SDOF ELASTIC- PLASTIC MODEL

 NOTE  DEFAULT UNITS ARE INCHES, POUNDS, AND SEC
       UNLESS OTHERWISE SPECIFIED

 AVAILABLE OPTIONS
   X - EXIT PROGRAM
   A - ANALYZE
   D - DISPLAY DATA
   H - HELP
   I - INITIAL PASS
   L - LOADING FUNCTION
   N - NUMERICAL PARAMETERS
   O - OUTPUT DEVICE
   P - PLOT
   S - SET VALUES FOR ANALYSIS
   T - TITLE

 SELECT OPTION: (X,A,D,H,I,L,N,O,P,S,T)
T
 ENTER NEW TITLE: (72 CHAR. MAX.)
SOLUTION FOR 0.3 SEC STRUCTURE AT 20 KT, 25 PSI
 SELECT OPTION: (X,A,D,H,I,L,N,O,P,S,T)
I
 SELECT SPEICHER-BRODE, TRIANGULAR,  OR EXIT: (S,T,X)
S
 ENTER WEAPON(KT):
20
 ENTER PEAK OVERPRESSURE:
25
 ENTER HEIGHT OF BURST(KFEET):
0

SOLUTION FOR 0.3 SEC STRUCTURE AT 20 KT, 25 PSI

      NUMERICAL PARAMETERS:
       BETA =   0.16667
       INTEGRATION INTERVAL =  0.10000E-01  OF PERIOD
       INTEGRATION INTERVAL =  0.10000E-01  OF DURATION
       TOLERANCE =  0.10000E-02
       NUMBER OF PRESSURE STATIONS =     250

      LOAD DESCRIPTION:
       WEAPON (KT)=   20.000
       PEAK OVERPRESSURE =    25.000
       POSITIVE PHASE DURATION =  0.44220
       TIME OF ARRIVAL =  0.51380
       RANGE (KFEET) =    1.7741
       HEIGHT OF BURST (KFEET) =  0.00000

 PRESSURE-TIME HISTORY? (Y/N)
N
```

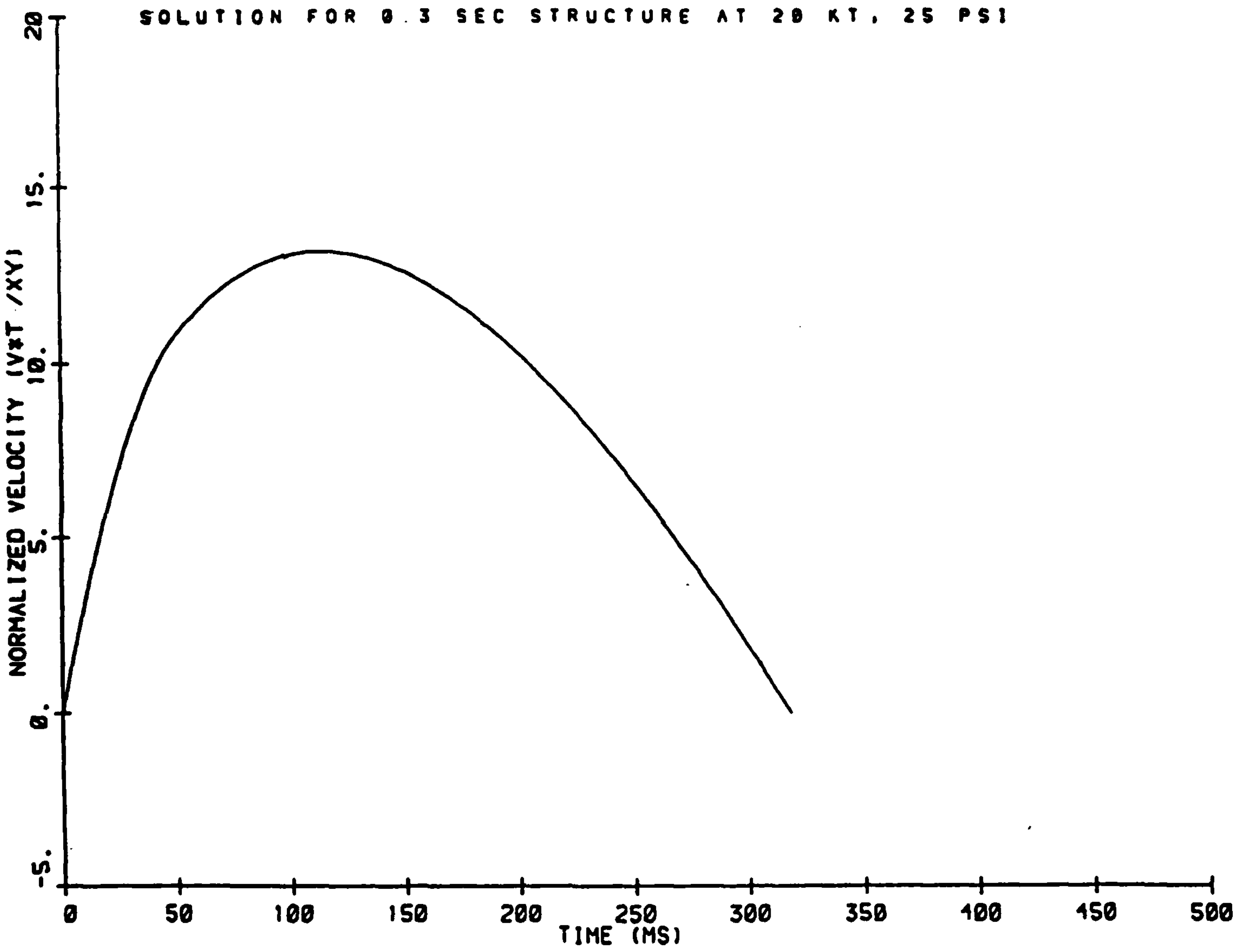
```
ENTER NATURAL PERIOD:
V 300
ENTER PEAK RESISTANCE:
10 0
SELECT OPTION: (X,A,D,H,I,L,N,O,P,S,T)
A

     MAXIMUM DUCTILITY =   0.3013
     OCCURS AT TIME =  0.31800
     NORMALIZED PRESSURE AT THIS TIME =  0.74042E-01

     NATURAL PERIOD =  0 30000
     LOAD DURATION =  0.44220
     TIME INCREMENT =  0.30000E-02

COMPLETE HISTORY? (Y/N):
Y

     NOTE: RESPONSES ARE NORMALIZED:
```

TIME	DISP	VEL	ACC
0.00000	0.00000	0 00000	98 60508
0.00300	0.00489	0.97249	95 88261
0.00600	0 01935	1 91468	92 03080
0.00900	0 04307	2 82375	89.18823
0.01200	0.07570	3.69715	85.40127
0.01500	0.11680	4.53233	81 54372
0.01800	0.16622	5 32682	77 35503
0.02100	0.22328	6.07831	72 94261
0.02400	0.28763	6.78481	68 31834
0.02700	0.35881	7.44367	63.49348
0.03000	0 43634	8.05357	58 48648
0.03300	0.51971	8.61258	53.31572
0.03600	0 60842	9.11913	47.99488
0.03900	0.70192	9.57188	42 54862
0.04200	0.79967	9 96940	36.97874
0.04500	0.90112	10.31091	31.32243
0.04800	1.00570	10.59668	25.61688
0.05100	1 11293	10.84702	24.26700
0.05400	1.22259	11.08217	22.76250
0.05700	1.33453	11.30249	21.38106
0.06000	1.44859	11.50841	19.88419
0.06300	1.56465	11.70037	18.50806
0.06600	1.68255	11.87876	17.16977
0.06900	1.80218	12.04396	15.86980
0.07200	1.92339	12.19634	14.60662
0.07500	2.04606	12.33626	13.37684
0.07800	2.17008	12.46405	12.18023
0.08100	2.29531	12.58003	11.01693
0 08400	2.42164	12.68453	9.88327
0.08700	2.54896	12.77784	8.77844
0.09000	2.67716	12.86025	7.70392
0.09300	2.80613	12.93205	6.65583
0.09600	2.93577	12.99350	5.63324
0.09900	3.06597	13.04485	4.63759
0 10200	3.19663	13.08637	3.66507

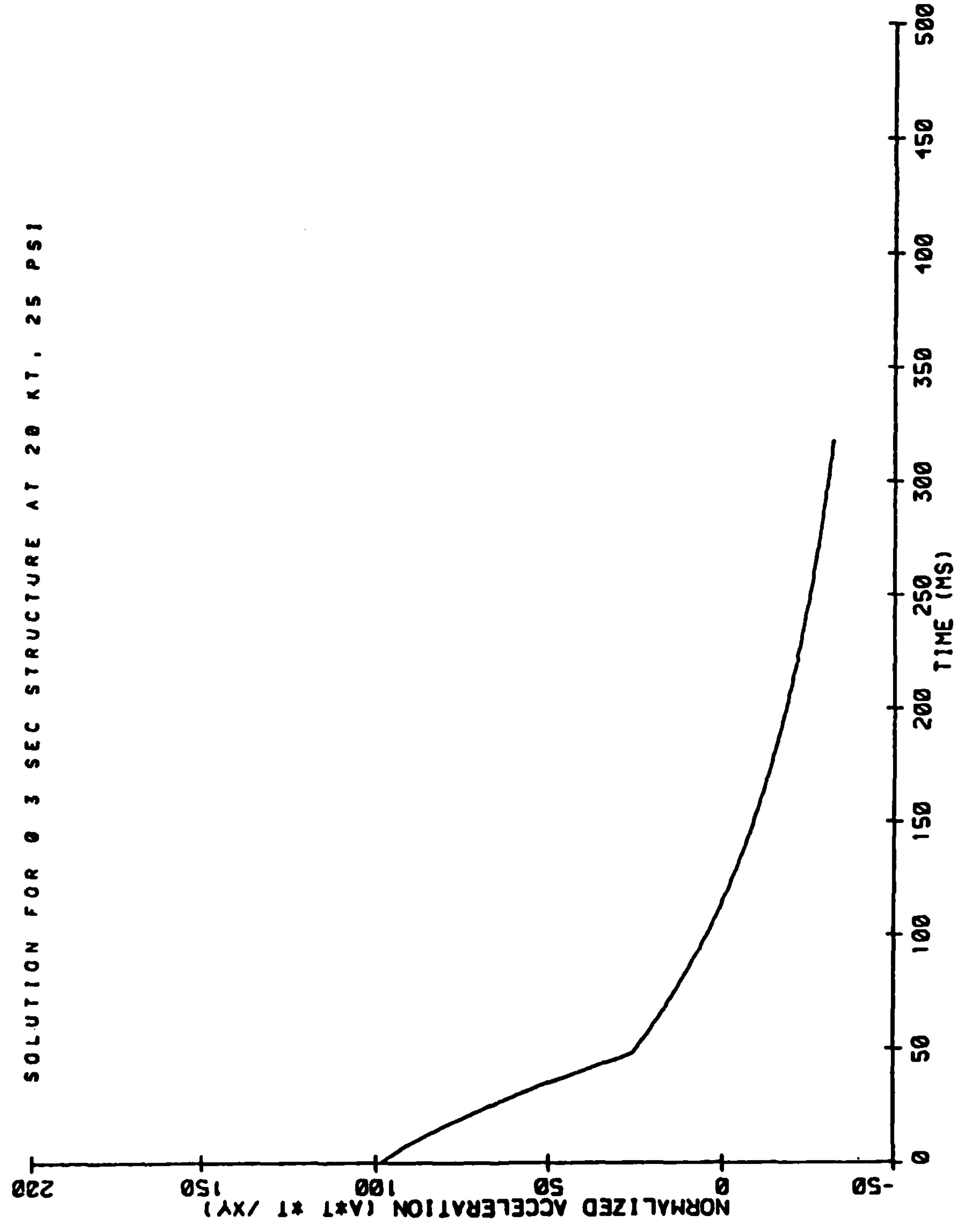
0.10500	3.32700	13.11829	2.71724
0.10800	3.45896	13.14083	1.79216
0.11100	3.59045	13.15424	0.88924
0.11400	3.72202	13.15872	0.00693
0.11700	3.85359	13.15448	-0.85453
0.12000	3.98508	13.14173	-1.69551
0.12300	4.11640	13.12067	-2.51789
0.12600	4.24747	13.09147	-3.32178
0.12900	4.37820	13.05432	-4.10670
0.13200	4.50853	13.00942	-4.87475
0.13500	4.63837	12.95691	-5.62636
0.13800	4.76764	12.89698	-6.36038
0.14100	4.89628	12.82978	-7.07981
0.14400	5.02421	12.75547	-7.78268
0.14700	5.15137	12.67421	-8.47061
0.15000	5.27768	12.58613	-9.14413
0.15300	5.40307	12.49139	-9.80402
0.15600	5.52748	12.39012	-10.44978
0.15900	5.65085	12.28246	-11.08204
0.16200	5.77311	12.16854	-11.70179
0.16500	5.89420	12.04849	-12.30886
0.16800	6.01406	11.92243	-12.90323
0.17100	6.13263	11.79048	-13.48611
0.17400	6.24985	11.65277	-14.05756
0.17700	6.36567	11.50939	-14.61708
0.18000	6.48002	11.36048	-15.16507
0.18300	6.59286	11.20612	-15.70450
0.18600	6.70412	11.04644	-16.23192
0.18900	6.61377	10.88154	-16.74944
0.19200	6.92174	10.71150	-17.25739
0.19500	7.02798	10.53644	-17.75525
0.19800	7.13245	10.35644	-18.24373
0.20100	7.23509	10.17161	-18.72333
0.20400	7.33587	9.98202	-19.19380
0.20700	7.43472	9.78778	-19.65533
0.21000	7.53161	9.58896	-20.10864
0.21300	7.62648	9.38565	-20.55363
0.21600	7.71931	9.17793	-20.99013
0.21900	7.81003	8.96588	-21.41898
0.22200	7.89861	8.74959	-21.84026
0.22500	7.98501	8.52912	-22.25343
0.22800	8.06918	8.30455	-22.65948
0.23100	8.15108	8.07596	-23.05852
0.23400	8.23068	7.84342	-23.45009
0.23700	8.30794	7.60699	-23.83485
0.24000	8.38281	7.36676	-24.21307
0.24300	8.45526	7.12277	-24.58446
0.24600	8.52525	6.87510	-24.94934
0.24900	8.59275	6.62381	-25.30811
0.25200	8.65772	6.36897	-25.66061
0.25500	8.72012	6.11063	-26.00687
0.25800	8.77992	5.84886	-26.34740
0.26100	8.83709	5.58371	-26.68219
0.26400	8.89158	5.31524	-27.01100
0.26700	8.94338	5.04352	-27.33444
0.27000	8.99244	4.76858	-27.65260
0.27300	9.03874	4.49049	-27.96504

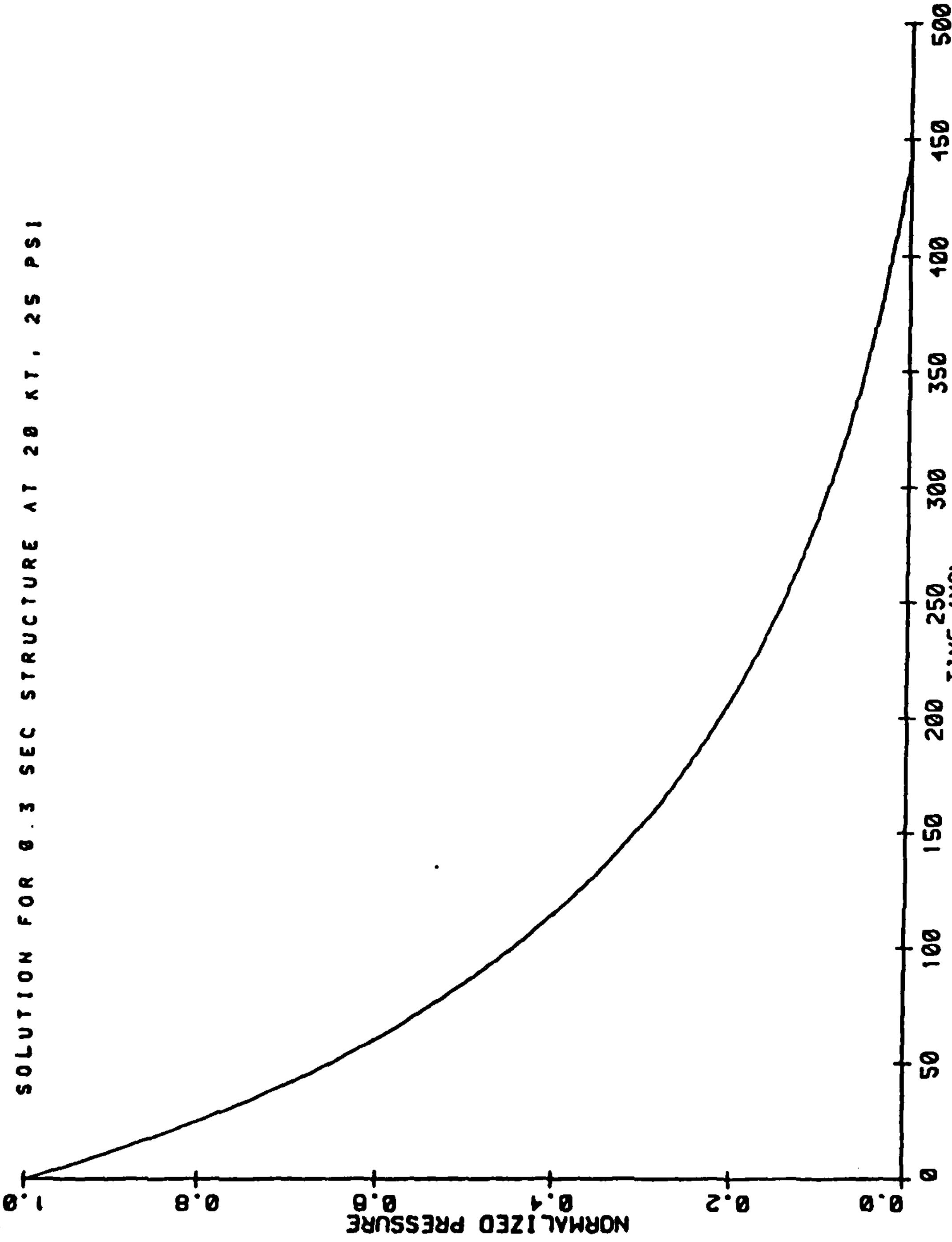
```
0 27000     9.08224     4 20931    -28.27242
0 27900     9.12292     3.92507    -28.57483
0 28200     9 16073     3.63784    -28.87199
0 28500     9 19566     3 34766    -29.16428
0 28800     9.22768     3.05457    -29.45198
0 29100     9.25075     2.75864    -29.73466
0 29400     9 28284     2.45990    -30.01278
0.29700     9.30593     2 15841    -30.28641
0 30000     9 32600     1 85420    -30 55566
0 30300     9 34301     1 54732    -30 82034
0 30600     9.35694     1.23781    -31 08089
0 30900     9 36776     0 92572    -31.33734
0 31200     9.37544     0 61109    -31 58939
0 31500     9 37997     0 29395    -31 83755
0 31800     9 38131    -0.02564    -32.08189
0 32100     9.37945    -0 34766    -32 32207

 SELECT OPTION: (X,A,D,H,I,L,N,O,P,S,T)
U

SOLUTION FOR 0.3 SEC STRUCTURE AT 20 KT, 25 PSI

     NUMERICAL PARAMETERS.
      BETA -    0 16667
      INTEGRATION INTERVAL -  0.10000E-01  OF PERIOD
      INTEGRATION INTERVAL -  0.10000E-01  OF DURATION
      TOLERANCE -  0.10000E-02
      NUMBER OF PRESSURE STATIONS -     250

     LOAD DESCRIPTION:
      WEAPON (KT)-    20.000
      PEAK OVERPRESSURE -    25 000
      POSITIVE PHASE DURATION -  0 44229
      TIME OF ARRIVAL -  0.51300
      RANGE (KFEET) -    1.7741
      HEIGHT OF BURST (KFEET) -  0 00000

     STRUCTURE DESCRIPTION:
      NATURAL PERIOD -  0.30000
      FREQUENCY -    3.3333
      PEAK RESISTANCE -    10 000

 PRESSURE-TIME HISTORY? (Y/N)
N
 SELECT OPTION: (X,A,D,H,I,L,N,O,P,S,T)
P
 SELECT PLOT  (D,V,A,L,X)
```


SOLUTION FOR 0.3 SEC STRUCTURE AT 20 KT, 25 PSI
NORMALIZED DISPLACEMENT (D/XY)
0.
.2
.4
.6
.8
10
TIME (MS)
0
50
100
150
200
250
300
350
400
450
500



SOLUTION FOR 0.3 SEC STRUCTURE AT 20 KT, 25 PSI
NORMALIZED VELOCITY (V*T /XY)
20
15.
10.
5.
0.
-5.
0
50
100
150
200
250
300
350
400
450
500
TIME (MS)


SOLUTION FOR 0.3 SEC STRUCTURE AT 20 KT, 25 PSI
NORMALIZED ACCELERATION (A*T *T /XY)
-50
0
50
100
150
200
TIME (MS)
0
50
100
150
200
250
300
350
400
450
500


SOLUTION FOR 0.3 SEC STRUCTURE AT 20 KT, 25 PSI
NORMALIZED PRESSURE
0.0
0.2
0.4
0.6
0.8
1.0
TIME (MS)
0
50
100
150
200
250
300
350
400
450
500

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APPENDIX C

NOTATION

NOTATION

f	Forcing function/maximum force
F	Forcing function
F_1	Maximum force
k	Elastic function
m	Structural mass
P_s	Peak overpressure
r	Structural resistance
r_m	Maximum resistance
t	Time
t_d	Positive phase duration of load
t_m	Time to maximum response
T	Natural period
x	Displacement
$\dot{x}$	Velocity
$\ddot{x}$	Acceleration
x_m	Maximum displacement
x_y	Yield or peak elastic displacement
β	Newmark β numerical parameter
Δt	Time increment
η	Normalized displacement
$\dot{\eta}$	Normalized velocity
$\ddot{\eta}$	Normalized acceleration
μ	Ductility
ξ	Normalized time parameter

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